DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES LIST

SECTION 16: POSITIONING, NAVIGATION AND TIME TECHNOLOGY

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PREFACE

The Defense Critical Technologies Program (DCTP) provides a systematic, ongoing assessment and analysis of goods and technologies to determine those that are critical to the Department of Defense (DoD). It characterizes the technologies (including quantitative values and parameters) and assesses worldwide technology capabilities.

The Militarily Critical Technologies List (MCTL) is a product of the DCTP. The MCTL is a compendium of goods and technologies that DoD assesses would permit significant advances in the development, production, and use of the military capabilities of potential adversaries. It includes goods and technologies that enable the development, production, and employment of weapons of mass destruction (WMD). Goods and technologies are considered critical if their acquisition and exploitation by a potential adversary would either significantly negate or impair a major military capability of the United States or significantly advance a critical military capability of the adversary. A leading edge technology that has a high potential for advanced military application can be included even if it is not currently embedded in a U.S. system.

Technologies are selected for the MCTL through the deliberation and consensus of Technology Working Groups (TWGs). TWG chairpersons continually screen technologies and nominate items to be added or removed from the MCTL. TWG members come from government, industry, and academia. Working within an informal structure, the TWGs strive to produce precise and objective analyses across the technology areas and to update these assessments periodically.

The legal basis of the MCTL stems from the Export Administration Act (EAA) of 1979, which assigned responsibilities for export controls to protect technologies and weapons systems. It established the requirement for DoD to compile a list of militarily critical technologies. The EAA and its provisions, as amended, have been extended by Presidential Directives.

The MCTL is not an export control list. Items on the MCTL may not be on an export control list, and items on an export control list may not be on the MCTL. The MCTL is designed to be used as a reference for evaluating potential technology transfers and for reviewing technical reports and scientific papers for public release. Technical judgment must be used when applying the information. The MCTL should be used to determine whether the proposed transaction would result in a transfer that would give potential adversaries access to technologies whose specific performance levels are at or above the characteristics identified as militarily critical. It should not be used to determine whether a transfer should or should not be approved.

SECTION 16—POSITIONING, NAVIGATION, AND TIME TECHNOLOGY

Scope

Highlights

- Inertial navigation system technologies provide an autonomous, covert, and nonjammable three-dimensional (3–D) position and velocity reference for military platforms. The number of military applications of hybrid inertial navigation systems with embedded Global Positioning System (GPS), differential GPS (DGPS), long-range aid to navigation (LORAN), Doppler, or data-based referenced navigation (DBRN) systems will continue to increase as the cost, weight, and size of the various systems continue to decrease.
- Low probability of intercept/low probability of detection (LPI/LPD) radar altimeters integrated with greatly improved terrain databases provide a military alternative to GPS, particularly in a jamming environment.
- GPS is the dominant worldwide standard for positioning, navigation, and time (PNT) dissemination. These capabilities improve combat situational awareness by providing position and time (POSITIME) of allied and enemy forces. The GPS is undergoing a modernization effort to improve performance in times of conflict and of peace.
- Precise time and frequency (PT&F) are required for autonomous operation of terrestrial and satellite geolocation systems and enhanced cryptographic (CRYPTO)/transmission secured (TRANSEC) performance in spread-spectrum systems. The importance of PT&F has only recently been recognized because of the availability and accuracy of GPS time.
- LORAN remains an option to disseminate accurate time and determine position for critical redundancy.
- Improvements in gravity meter and gradiometer arrays and satellite sensor systems provide increased detection and location of submarines, mines, tunnels, and mobile missile launchers.
- Magnetic and electromagnetic sensor and array technology for covert detection and classification is evolving because of better sensors, advances in processor speed and memory capacity, and integration with PT&F devices and geo databases.
- Emerging radio-frequency identification (RFID) technology, using secure, encrypted, millimeter waveform could become the primary cooperative North Atlantic Treaty Organization (NATO) identification friend or foe (IFF) capability in the ground battlespace for the foreseeable future.

OVERVIEW

This section covers technologies for both autonomous and cooperative PNT systems for the coordination and control of military force elements. Most of these technologies have dual-use requirements, and all of them are essential for various military missions. All of them are dependent on good power and environmental control systems.

Section 16.1 includes inertial systems and components that form the basis for autonomous, covert navigation and motion sensing. Included are inertial navigation systems, various types of integrated or hybrid inertial navigation systems, and many distinct types of gyroscopes and accelerometers that can be found in a navigation system. Also included are gyro astro trackers and azimuth determination systems that require gyroscopic systems for a stable level reference. Technologies below the gyroscope and accelerometer sensor level (i.e., fiber-optic cables) are included in Section 10, Information Technology. Hybrid systems bound the time-dependent errors of the inertial sensors. Accuracy of position and time provides a more robust navigation system. Further improvements in hybrid inertial navigation system performance are expected.

Section 16.2 includes both gravity meters and gravity gradiometers used in either static or moving-base measurements. Continuing improvements in gravity sensors are enabling better inertial navigation system error compensation, strategic arms treaty verification, and detection of tunnels and terrain estimation.

Section 16.3 covers a limited category of militarily critical radio and DBRN technology and systems having a wide range of dual-use applications. The U.S. GPS consists of three segments: (1) space systems (including satellites), (2) satellite command and control systems, and (3) user receivers and associated equipment. Only the last is included in this section; refer to Section 19, Space Systems Technology for (1) and (2). Over the past 4 years, GPS receiver technology has exploded. Primarily driven by the commercial markets, these advances have resulted in significant cost and size reduction and increased the ratio of commercial to military users dramatically. This rate of growth is expected to increase, particularly with President Clinton's decision on 1 May 2000 to discontinue the intentional degradation [selective availability (S/A)] of GPS signals for civilian users. This section also covers Differential Global Navigation Satellite System (DGNSS) receivers and hybrid radio navigation receivers. These include Global Navigation Satellite System (GNSS), LORAN and Doppler, Joint Tactical Information Distribution System (JTIDS), Enhanced Position Locating Reporting System (EPLRS), or DBRN (including 3–D digital terrain maps, other geomapping databases, and acoustic, stellar, gravity, and magnetic databases). Other technologies included in this section are LPI/LPD Doppler/sonar navigation systems and radar altimeters/fathometers, as well as radio direction-finding equipment.

Section 16.4 covers the technology relative to magnetometers of various types, including active electromagnetic sensors, underwater electric field sensors, magnetic gradiometers, and arrays composed of magnetic and electric field sensors. Magnetic sensor systems detect and display the presence of a magnetic field and measure its magnitude or direction. Magnetic sensor types of special interest include supercomputing quantum interference device (SQUID), nuclear precession, optically pumped, induction coil, flux gate, fiber optic, and magnetoresistive. Magnetic sensor systems can be configured to detect the spatial variation of the magnetic field intensity from sources external to the instrument, that is, the gradient of the magnetic field intensity. In this mode they are called magnetic gradiometers. For details on the use of magnetic sensors for mine countermeasures, refer to Section 17, Sensors.

Section 16.5 is divided into four PT&F technology areas: time distribution, atomic/ion and laser clocks (used in ground stations and satellites), low-power clocks and oscillators (used in receivers), and optical clocks. Most types of positioning and navigation (POSNAV) systems are highly dependent on precise time, but other applications depend on frequency and not absolute time (refer to Section 16.3 for GPS and LORAN as timing distribution systems).

Section 16.6 covers combat identification (CID) technologies that specifically involve the positive, timely, and reliable identification and classification of friends, foes, and neutrals from cooperative or noncooperative systems. Both cooperative and noncooperative systems provide the warfighter with discrimination between targets and nontargets in the battlespace. A cooperative identification (ID) system requires either: (1) a question and answer (Q&A) system or (2) use of visual or other devices on the target that can be seen by the warfighter. This technology has a high confidence of identifying "friendlies." A noncooperative ID system provides the warfighter with an autonomous capability to identify and classify the target as a “foe,” as well as a “friend” or a “neutral.” Automatic target recognition (ATR) and multisensor fusion technologies are addressed in this section. Critical parameters for specific sensors that could be used for target detection are addressed in Section 11, Lasers and Optics, and Section 17, Sensors. Also other related command, control, and communication (C3) CID technologies are addressed in Section 10, Information Technology.

BACKGROUND

Over the past 10 years, PNT technologies have been highly affected by advances in computer throughput, memory, and algorithms, as well as miniaturization and reliability of electronic components. These technologies, in turn, have been highly influenced by advances in material, manufacturing, and fabrication technologies. The applications of satellite PNT technologies, particularly the U.S. GPS, has had an enormous positive impact on military and commercial users, especially the telecommunications industry, which has had a need for accurate time to efficiently use the frequency spectrum. The following Web site provide general information on navigation and positioning, its history, and its instruments:

http://www.utexas.edu/depts/grg/classes/crum/grg309/notes/position/sld001.htm

SECTION 16.1—INERTIAL NAVIGATION SYSTEMS AND RELATED COMPONENTS

Highlights

- Inertial navigation system technologies provide an autonomous, covert, and nonjammable 3–D position, attitude, heading, and velocity reference for military platforms.
- The performance levels for commercial and military (aircraft and ground use) inertial navigation systems have stayed at their respective levels of 2.0 and 0.8 nmi/hr over the last 20 years. However, size, weight, reliability, and cost have all improved.
- Fiber-optic gyroscope technology has been in production at the tactical level (1–30 deg/hr) for over 5 years, and it is now entering production for navigation-grade systems.
- Major reductions in manufacturing complexity, size, and cost of inertial sensors are being realized by use of MEMS sensors, electronics, and radio frequency interfaces for tactical reference (midcourse guidance and pointing).
- Military application of hybrid inertial navigation systems with embedded GPS, DGPS, LORAN, Doppler, and/or DBRN systems have increased over the past 10 years and will continue to increase as their cost, weight, and size improve.
- Built-in redundancy through low-cost, small-size, lightweight, and highly reliable components is moving in a direction that could allow an affordable, throwaway logistics concept. This will enable a rapid and affordable technology insertion of emerging inertial navigation system technology.

OVERVIEW

This section of PNT includes inertial systems and components that form the basis for autonomous, covert navigation and motion sensing. Included are inertial navigation systems, various types of integrated or hybrid inertial navigation systems, and each of many distinct types of gyroscopes and accelerometers that can be found in a navigation system. Multifunction linear and angular or rotational accelerometer components are also included. Inertial measurement units are a subassembly of an inertial navigation system, which traditionally consists of gyroscopes, accelerometers, a mounting structure, and supporting electronics. The inertial measurement unit provides delta-angle (sometimes referred to as delta theta) and delta velocity outputs for use by the vehicle or the system performing the navigation. Synonymous terms include, but are not limited to, inertial reference unit, inertial sensor assembly, and inertial sensor unit. These subassemblies have the militarily critical parametric levels of the inertial instruments (gyroscopes and accelerometers) used therein. An attitude and heading reference system (AHRS) provides attitude and magnetic heading, but does not necessarily provide a complete navigation solution. An AHRS may also provide velocity, angular rate, and acceleration data. An AHRS is controlled at the level of the inertial instruments (gyroscopes and accelerometers) used therein. Both gyro astro trackers and azimuth-determination systems require gyro systems for reference (level). Not included in this section are technologies below the gyroscope and accelerometer sensor level (i.e., fiber-optic cables).

The 2001 Federal Radionavigation Plan[1] notes civil navigation applications.

[1] Federal Radionavigation Plan, http://www.NAVCEN.uscg.gov/pubs/FRP2001/FRP2001.pdf

BACKGROUND

An inertial navigation system is a self-contained system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. An inertial navigation system contains accelerometers and gyroscopes to sense linear and angular rate. The system can be mechanized as a gimbaled platform, as a strapdown inertial sensing unit employing a computer to provide the “software” equivalent of gimbals, or as a hybrid unit with both gimbal and strapdown features. Hybrid systems bound the time-dependent errors of the inertial sensors or systems, resulting in a more robust nonjammable navigation system. Further improvement in hybrid inertial navigation system performance is expected to continue. Hybrid/DBRN also provides an accurate autonomous, nonjamming, and covert navigation capability, independent of any GNSS. A gyro astro tracker or astro compass is an automated optical or radiometric sextant that tracks selected stars and provides true heading and position data by triangulation using the referenced stars. The system can operate day or night very accurately. The system requires a stable reference to level and is composed of components of, or hybridized with, an inertial navigation system.

LIST OF MCTL TECHNOLOGY DATA SHEETS
16.1. INERTIAL NAVIGATION SYSTEMS AND RELATED COMPONENTS

MCTL DATA SHEET 16.1-1. INERTIAL NAVIGATION SYSTEMS

Critical Technology Parameter	Any inertial navigation system (gimbaled or strapdown) and inertial equipment designed 1. For aircraft, land vehicles, missiles, ships, submersibles, or spacecraft, for position, velocity, attitude, guidance, or control, having a navigation error (free inertial) after normal alignment/calibration (less than 8 min) of 0.8 nmi/hr (CEP) or less (better); or 2. For any of the above, having an azimuth accuracy of less (better) than 10 arc minutes times the secant of latitude; or 3. Capable of functioning at continuous acceleration levels exceeding 10 g on any platform. 4. Specified to have a non-operating shock level of 100-g or greater at a duration of between 1 millisecond and 1 second inclusive.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components requiring specially designed test, calibration, or alignment equipment for test, calibration, alignment, or production. Ship-motion simulator capable of motion with three or more simultaneous degrees of freedom.
Unique Software	Software specially designed or modified to improve the operational performance or reduce navigational error to the levels specified above. Source code for inertial navigation system for autonomous use. Source code, algorithms, and verified data needed to meet militarily critical parameters. Software for optimizing inertial navigation system alignment time for moving platforms and transfer alignment techniques. Algorithms for gyro compensation.
Major Commercial Applications	Aviation, ships, space, and land vehicles.
Affordability Issues	Accuracy is a cost driver. Reduced costs are attendant with strapdown systems and production base.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII; CCL Cat 7.

BACKGROUND

The inertial navigation system is made from a navigation computer and a set of gyroscopes and accelerometers, generally called inertial sensors, that measure in Newton's inertial axes. Gyroscopes measure rotation, and accelerometers measure acceleration. Integrating the output from an accelerometer gives speed, and integrating speed gives distance traveled. The gyroscopes provide information on where the accelerations are directed, and therefore heading and distance, the essential ingredients for dead reckoning, are known.

The group of inertial sensors is commonly called an inertial measurement unit, an inertial reference unit, an inertial sensor assembly, or an inertial sensor unit. An AHRS provides attitude and magnetic heading, but does not provide a complete navigation solution. An AHRS may provide velocity, angular rate, and acceleration data in addition to attitude and heading. This system may be combined into hybrid systems to complete the navigation function. The inertial sensors might be mounted in a set of gimbals so that they stay level in a fixed direction no matter how the vehicle moves. This is called a *gimbaled* system. As an alternative, the instruments might be attached to the vehicle, in which case they measure its motion components in the vehicle axes by transforming the measurements from the vehicle axes to the reference axes. This is called a *strapdown* system. Because these instruments use inertial properties of matter (or of light) for their operation, dead reckoning with gyroscopes and accelerometers is called *inertial navigation*.[2]

[2] Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-2. HYBRID INERTIAL NAVIGATION SYSTEM (INCLUDING GNSS)

Critical Technology Parameter	Any hybrid (the terms "hybrid" and "integrated" are the same) inertial navigation system (gimbaled or strapdown) having any of the following characteristics and specifically designed components therefor: 1. Integrated or embedded with any single or combination of navigation sources [Doppler (sonar, laser, or radar), LORAN, Air Data, GNSS, or DBRN (acoustic, stellar, gravity, and magnetic databases], and/or 3–D digital terrain maps and other geomapping data) having a position accuracy of less (better than) 10 m CEP; or 2. After loss of GNSS, having, for a period of up to 4 min, a position accuracy of less (better) than 10 m CEP, or a navigation drift rate of less (better) than 0.8 nmi/hr or a velocity accuracy of less than 0.1 m/s; or 3. Capable of functioning at continuous acceleration levels exceeding 10 g on any platform; or 4. Having an azimuth accuracy of less (better) than 10 arc minutes times secant of latitude; or 5. Any GNSS receiver equipment that has the following characteristics: a. Uses military cryptographic modules, integrated circuits, or components of software designed for generating the GPS Y-code signal for the purpose of information security and key management; uses active and passive antijam systems with the ability to respond to incoming interference (null steering antenna), generate a high-gain beam towards the GPS satellite; or uses suppression technology to reduce jamming signals; is designed or modified for use with active and passive countermeasures and counter-countermeasures; and has encrypted GPS/transponder integration capability; or b. Designed for producing navigation results above altitudes of 60,000 ft and at velocities exceeding 1,000 knots; or c. Designed or modified for use with unmanned vehicles. 6. Specified to have a non-operating shock level of 100-g or greater at a duration of between 1 millisecond and 1 second inclusive.
Critical Materials	Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic.
Unique Test, Production, Inspection Equipment	Components that require specially designed test, calibration, or alignment equipment. GNSS receivers that require use of military-capable, signal-simulator testing systems. Systems that simulate/generate the specialized radio-frequency signal and data message structure and require the use of U.S. cryptography. Any antispoofing signal simulators.
Unique Software	Software specially designed or modified to meet militarily critical parameters. Source code for inertial navigation systems for hybridized use. Source code, algorithms, and verified data needed to exceed militarily critical parameters with any of following navigation data: Doppler radar or sonar, LORAN, Air Data, GNSS, or DBRN (acoustic, stellar, gravity, and magnetic databases, or 3–D digital terrain maps and other geomapping data). Source code for integrated avionics or mission systems that combine sensor data and employ expert systems.

Major Commercial Applications	Aviation, ships, space, and land vehicles.
Affordability Issues	Not an issue.

BACKGROUND

An inertial navigation system provides very accurate attitude and distance measurement, but errors from the gyroscope and accelerometer accumulate over time. Navigation errors therefore also grow as a function of time. Other navigation systems, such as GNSS, Doppler, LORAN, or DBRN, are not affected by time. Integrating any combination of these systems with an inertial navigation system, which results in a system called a *hybrid inertial navigation system,* provides a very accurate navigation system independent of time. An inertial navigation system also provides a "flywheel" effect for continuous accurate navigation, even when these other navigation signals are lost (intentionally or not).

The following is a list of associated references or useful Web sites:

Dr. G.T. Schmidt, Draper Lab, *GPS/INS Technology Trends for Military Systems,* 1997.

http://www.gpsworld.com/gpsbuyers/prod10047.htm

http://www.base-usa.com/terpfact.htm

http://www.aerotechnology.com/04d.htm

http://www.mne.ksu.edu/afsl/data_fusion.htm

http://www.boeing.com/defense-space/infoelect/insgps/migits.htm

http://www.imar-navigation.de/englishside/dat_engl/idrpos_e.htm

MCTL DATA SHEET 16.1-3. GYRO ASTRO-TRACKING DEVICES

Critical Technology Parameter	Any gyro astro-tracking device (also called a star tracker or stellar compass) having the following characteristics: 1. An azimuth accuracy equal to or less (better) than 5 seconds of arc, or 2. Capable of functioning at continuous acceleration levels exceeding 10 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment including clock accuracy of a microsecond per 24 hours. Star simulators required.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Source code for combining an inertial navigation system with a gyro astro tracker is unique. Gyro astro tracker stabilization requires accurate initialization and reference data from an inertial navigation system.
Major Commercial Applications	None identified.
Affordability Issues	Very expensive because of low volume requirements and technical complexity.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

Gyro astro-tracking devices or star trackers are a type of telescope on a stable (gyroscopic) platform with an optical detector array at its focus, which can be precisely pointed at a star whose location is known. This star tracker locks onto the preselected star and uses the star's known position to determine the vehicle's position. These devices are immune from jamming, but are affected by atmospheric turbulence, such as smoke and haze. Star trackers are expensive and require a window in a vehicle.[3]

The following Web site describes a star tracker stellar compass for providing inertial reference for a spacecraft:

http://www.llnl.gov/sensor_technology/STR45.html

[3] Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-4. AZIMUTH (NORTH-POINTING) DETERMINATION SYSTEMS

Critical Technology Parameter	Any azimuth, or north-pointing, determination system (includes compass systems) having an azimuth or pointing accuracy of less (better) than 10 arc minutes times secant of latitude.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed for compensation.
Major Commercial Applications	Satellite communications, bore sighting, geodesy, surveying, and construction.
Affordability Issues	Not an issue.
Export Control References	WA ML 9; WA Cat 6,7; MTCR 9; USML XII, XV; CCL Cat 7.

BACKGROUND

Azimuth, or north-pointing, systems use gyroscopes to precisely determine the orientation of the vehicle with respect to true geographic north. The rate gyroscope is used to measure Earth's rotation rate (approximately 15 deg/h at the equator); this value is then used to compute the angle (of the vehicle) with respect to true north. The only external input required is the approximate latitude. This system offers a significant improvement over magnetic measurement techniques, which are susceptible to local anomalies in Earth's magnetic field, distortion caused by ferrous metals, and currents in the equipment to which it is mounted.

The following is a list of associated or useful Web sites:

http://www.astronautics.com/Products/Default.asp?50.42.0

http://kvh.com/products/sensor/nfog/nfog.html

http://www.kvh.com/products/military/sensors/nfog.html

http://www.smithsind-aerospace.com/PRODS/NGS/nfm.htm

MCTL DATA SHEET 16.1-5. GENERIC GYROSCOPES

Critical Technology Parameter	Any gyroscope having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of: 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	The unique equipment depends on the specific gyro technology, and reference should be made to the specific technology data sheet.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	Aviation, ships, land and space vehicles, robotics, manufacturing, and stability reference (cameras, telescopes, etc.).
Affordability Issues	Accuracy is a cost driver. Reduced costs are attendant with optical gyroscopes. Use of MEMS will further reduce cost of gyroscopes.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

Recent developments in gyroscope technology (i.e., ring laser gyroscopes, fiber-optic gyroscopes, and MEMS) have resulted in the IEEE proposing a new definition of gyroscopes, from “a device using angular momentum (usually of a spinning rotor)” to “an inertial sensor that measures angular rotation with respect to inertial space about its input axis(es). The sensing of such motion could utilize the angular momentum of a spinning rotor, the Coriolis effect on a vibrating mass, or the Sagnac effect on counter-propagating light beams in a ring laser or an optical fiber coil.” A planar waveguide is also a possibility.

The following is a list of associated references or useful Web sites:

Anthony Lawrence, *Modern Inertial Technology,* 1998.

http://230nsc1.phy-astr.gsu.edu/hbase/gyr.html

MCTL DATA SHEET 16.1-6. FLOATED GYROSCOPES

Critical Technology Parameter	Any floated gyroscope having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of: 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Gyro tuning test and dynamic balance station. Gyro run-in motor test station. Evacuation and fill stations. Centrifuge fixtures for gyro bearings.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	Aviation, ships, and land and space vehicles.
Affordability Issues	Not an issue.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

Learning from magnetic compasses and earlier German works, Draper Labs applied Archimedes' principle[4] to the single-degree-of-freedom gyroscope by sealing the gyro wheel and "floating" the gimbal in a fluid. This took the load off the output axis bearings to make their friction torque very low and resulted in very sensitive gyroscopes. Since fluid density varies with temperature, a perfectly floated gyroscope had to be heated, typically to about 60–80 °C, to reach flotation temperature. In the 1960s and 1970s it was considered normal to heat gyroscopes before gyrocompassing.[5]

The following is a list of associated references or useful Web sites:

Anthony, Lawrence, *Modern Inertial Technology,* 1998.

http://230nsc1.phy-astr.gsu.edu/hbase/gyr.html

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4 http://230nsc1.phy-astr.gsu.edu/hbase/hframe.html

5 Anthony Lawrence, *Modern Inertial Technology*, 1998.

MCTL DATA SHEET 16.1-7. DYNAMICALLY TUNED GYROSCOPES

Critical Technology Parameter	Any dynamically tuned gyroscope having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of: 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Gyro tuning test and dynamic balance station. Gyro run-in motor test station. Centrifuge fixtures for gyro bearings.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	Aviation, land and space vehicles, robotics, and manufacturing.
Affordability Issues	Not an issue.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

In the 1940s, engineers at the University of Edinburgh, Scotland, designed a gyroscope that used a spinning flywheel on a universal (Hooke's) joint. The gyroscope was surprisingly unstable, showing that the dynamic inertial effect of the gimbal in the universal joint was responsible.[6]

The following Web sites provide a few examples of this technology:

http://www.primenet.com/~watgyro/Ramenskoye/products/gvk-6.html

http://www.smithsind-aerospace.com/PRODS/NGS/series_2000_dynamically_tuned_gy.htm

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6 Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-8. ELECTROSTATICALLY SUPPORTED GYROSCOPES

Critical Technology Parameter	Any electrostatically supported gyroscope having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of: 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	Beryllium.
Unique Test, Production, Inspection Equipment	Gyro dynamic balance station.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	None identified.
Affordability Issues	Extremely costly because production will be low and tolerances high.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

In 1954, Arnold Norsieck invented the electrically supported gyroscope. This gyroscope uses a beryllium sphere (supported inside a spherical ceramic cavity) suspended by the electric field from electrodes placed along the three principal axes. The cavity is evacuated, raising the electrical breakdown threshold between the electrodes and the ball. When the sphere has spun up to typically 150,000 rpm, the motor is turned off and the rotor coasts. The electrical field forces, to maintain operating speed of the sphere, determine the gyro bias drift. This gyroscope is capable of drift performance well below 0.0001 deg/h. The precision of fabrication and the high quality needed to maintain the high vacuum make this a very expensive gyroscope. [7]

[7] Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-9. HEMISPHERICAL RESONATOR GYROSCOPES

Critical Technology Parameter	Any hemispherical resonator gyroscope (also called a wineglass or acoustic gyroscope) having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of: 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	None identified.
Affordability Issues	Extremely costly because of low production quantities; cost decreases as production increases.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

Lord Rayleigh, in his *Theory of Sound* (1894), analyzed the vibration patterns of plates and shells and referred to work published by a colleague, G.H. Bryan, concerning the effects of rotation on the nodal patterns of vibrating shells. Bryan wrote:

> If we select a wineglass which when struck gives, under ordinary circumstances, a pure and continuous tone, we shall on twisting it round hear beats, thus showing that the nodal meridians do not remain fixed in space. And if the observer will turn himself rapidly round, holding the vibrating glass all the time, beats will be heard, showing that the nodal meridians do not rotate with the same angular velocity as the glass and observer. We can therefore measure the precession of the nodes relative to an axis fixed to the shell and derive rate from it.

The hemispherical resonator gyroscope is a fused-quartz hemispheric vibrating shell supported by a stem along a diameter, like a wineglass with its stem continued into the bowl. The hemispherical resonator gyroscope shell is electrostatically excited at its natural frequency by an alternating current (AC) signal applied to fixed electrodes on the case. A servo system drives the shell to resonance and maintains the oscillation amplitude constant. Because the internal damping of quartz is so low and the enclosure is evacuated, little energy needs to be supplied to maintain resonance. The hemispherical resonator gyroscope continues to resonate when power is removed. Thus it "remembers" rotations occurring while it is temporarily unexcited. This memory could be useful in guidance systems for missiles that have to operate near nuclear blasts. The hemispherical resonator gyroscope is expensive to manufacture because its performance comes from the precise manufacturing of the shell and housing and the high vacuum sealing.[8]

The following is a list of associated or useful Web sites:

Anthony Lawrence, *Modern Inertial Technology,* 1998.

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[8] Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-10. RING LASER GYROSCOPES

Critical Technology Parameter	Any ring laser gyroscope having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of: 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Scatterometer accuracy of 10 ppm or less (better). Profilometer accuracy of 5 Å or less (better).
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	Aviation, ships, land and space vehicles, and robotics.
Affordability Issues	High cost for initial national capability because clean rooms and ultra-clean, high-vacuum equipment are required. High production base will reduce cost.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

Invented in the 1960s, the ring-laser gyroscope is an active-resonator optical gyroscope. A laser, the optical oscillator, is used as the light source. When used in a Fabry-Perot resonator with three or more mirrors making the light circulate through an enclosed-glass, waveguide medium, a beam splitter is used to provide clockwise and counterclockwise light beams. Both clockwise and counterclockwise waves will be generated; these will resonate when the path perimeter is an integral number of wavelengths, and the two waves will form a standing-wave pattern. Such a laser is called a ring laser.

As the ring-laser gyroscope is rotated about an axis normal to the resonator plane, the difference in transit time (or frequency shift) of the light beam traveling in opposite directions is proportional to the rotation rate. This is called the Sagnac effect.[9] Ring-laser gyroscopes are replacing conventional spinning-mass gyroscopes in many inertial navigation system applications because of their stability, high accuracy, high reliability, and low costs.

The following is a list of associated references or useful Web sites:

Anthony Lawrence, *Modern Inertial Technology,* 1998.

http://wseweb.ew.usna.edu/wse/academic/courses/es300/supplem/rlg.htm

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9 Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-11. FIBER-OPTIC GYROSCOPES

Critical Technology Parameter	Any fiber-optic gyroscope having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of: 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding□100 g on any platform.
Critical Materials	None identified. Available from multiple sources worldwide.
Unique Test, Production, Inspection Equipment	Fiber-winding machines.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	Aviation, ships, land and space vehicles, robotics, manufacturing, and stability reference (cameras, telescopes, etc.).
Affordability Issues	Use of polarization-maintaining fiber is a cost driver; however, alternatives exist.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

Like the ring laser gyroscope, the fiber-optic gyroscope was also invented in the 1960s, but developed more slowly. Its development tracked the communications industry light source and optical fiber developments. A fiber-optic gyroscope uses the Sagnac effect to determine rotation rate. The Sagnac effect results from the counter-propagation of light beams in an optical waveguide consisting of a coil of optical fiber, where the number of turns and diameter affect the accuracy of rotation-rate measurement. The difference of frequency is the optical reciprocity between clockwise and counterclockwise paths of the light beams. Rotation normal to the waveguide upsets the symmetry, which is then photoelectronically detected and processed to provide an indication of rotation rate.

The fiber-optic gyroscope is less expensive, lighter, and smaller than the ring laser gyroscope, and it may have a longer life and be more rugged. While the ring laser gyroscope blazed the trail (of optical gyroscopes) by demonstrating high performance and very long life, the fiber-optic gyroscope is just now being used in guidance-and-control systems, where it is challenging the ring laser gyroscope. In fact, the fiber-optic gyroscope has already displaced the ring laser gyroscope in some applications where gyro drift of 1 deg/h is acceptable.[10]

The following is a list of associated references or useful Web sites:

Anthony Lawrence, *Modern Inertial Technology,* 1998.

Dr. G.T. Schmidt, Draper Lab, *GPS/INS Technology Trends for Military Systems,* 1997.

Neil Barbour and Dr. G.T. Schmidt, Draper Lab, "Inertial Sensor Technology Trends," *IEEE*, 1998.

http://wseweb.ew.usna.edu/wse/academic/courses/es300/supplem/rlg.htm

http://www.imar-navigation.de/englishside/dat_engl/tgacrqe.htm

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[10] Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-12. MICROELECTROMECHANICAL SYSTEMS GYROSCOPES

Critical Technology Parameter	Any MEMS gyroscope having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of: 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment. Gyroscope axis alignment fixture. The fabrication process relies on commonly available semiconductor process equipment, including high-precision lithography, ion milling, plasma arc, and electronic-sputtering production equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Vehicle control and robotics.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

A MEMS gyroscope is usually designed as an electromechanically driven resonator, often fabricated out of a single piece of quartz or silicon. Such gyroscopes operate in accordance with the dynamic theory that when an angle rate is applied to a body, a Coriolis force is generated. When this angle rate is applied to the axis of a resonating tuning folk, its prongs receive a Coriolis force proportional to the applied angular rate. This force can be measured capacitively (silicon) or piezoelectrically (quartz).[11]

Many manufacturers are developing these MEMS accelerometers and gyroscopes to reduce the cost of these sensors.

The following is a list of associated references or useful Web sites:

Anthony Lawrence, *Modern Inertial Technology*, 1998.

Dr. G.T. Schmidt, Draper Lab, *GPS/INS Technology Trends for Military Systems*, 1997.

"Tiny Inertial Sensors Made on Silicon Chips," *Aviation Week & Space Technology,* August 10, 1998.

LtCol B.M. Kaspar, DARPA, *The DARPA MEMS Inertial Navigation System Program*, undated.

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[11] Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-13. GENERIC LINEAR ACCELEROMETERS

Critical Technology Parameter	Any linear accelerometer having the following characteristics: 1. A bias stability of less (better) than 130 μg with respect to a fixed calibration value over a period of 1 month; or 2. A scale factor stability of less (better) than 130 ppm with respect to a fixed calibration value over a period of 1 month; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment. Accelerometer axis-alignment stations and programmable dividing head.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Aviation, ships, land and space vehicles, robotics, manufacturing reference, geodesy, and seismic detection.
Affordability Issues	Not an issue, except for extremely accurate sensors with low quantity requirements.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

A basic linear accelerometer is a single-degree-of-freedom accelerometer made up of at least the following elements:

1. A mass, often called the "proof mass";
2. A suspension, which locates the mass; and
3. A pickoff, which puts out a signal related to the acceleration sensed.

There are two types of linear accelerometers, open loop and closed loop. The former will have a mass on a spring hinge as the sensing element. This is called an open-loop pendulous accelerometer. A pickoff will measure the angular deflection of the sensing element, and this is the accelerometer's output. Because of this deflection, the accelerometer can suffer from cross-coupling acceleration and vibrations. Open-loop accelerometers are satisfactory where dynamic range does not exceed 5,000 to 1 and where scale-factor error can be 0.1 percent or more.

Where higher performance is needed, it is better to use a closed-loop pendulous accelerometer. The closed-loop sensor relies on the feedback system to restrain the sensitive element under high acceleration and rotations. Closed-loop pendulous accelerometer designs vary with different kinds of materials and sensitivities of the core three elements.[12]

Refer to the other technology data sheets for different types of linear accelerometers. The following is a useful Web site to review basic accelerometer fundamentals:

http://webug.physics.uiuc.edu/courses/phys111/summer98/Lectures/Lect06/sld001.htm

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12 Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-14. LINEAR ACCELEROMETERS (OTHER THAN MICROMACHINED)

Critical Technology Parameter	Any linear accelerometer having the following characteristics: 1. A bias stability of less (better) than 130 µg with respect to a fixed calibration value over a period of 1 month; or 2. A scale factor stability of less (better) than 130 ppm with respect to a fixed calibration value over a period of 1 month; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment. Accelerometer axis-alignment stations and programmable dividing head.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Aviation, ships, land and space vehicles, robotics, manufacturing reference, geodesy, and seismic detection.
Affordability Issues	Not an issue, except for extremely accurate sensors with low quantity requirements.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

A basic linear accelerometer is a single-degree-of-freedom accelerometer made up of at least the following elements:

1. A mass, often called the "proof mass";
2. A suspension, which locates the mass; and
3. A pickoff, which puts out a signal related to the acceleration sensed.

There are two types of linear accelerometers, open loop and closed loop. The former will have a mass on a spring hinge as the sensing element. This is called an open-loop pendulous accelerometer. A pickoff will measure the angular deflection of the sensing element, and this is the accelerometer's output. Because of this deflection, the accelerometer can suffer from cross-coupling acceleration and vibrations. Open-loop accelerometers are satisfactory where dynamic range does not exceed 5,000 to 1 and where scale-factor error can be 0.1 percent or more.

Where higher performance is needed, it is better to use a closed-loop pendulous accelerometer. The closed-loop sensor relies on the feedback system to restrain the sensitive element under high acceleration and rotations. Closed-loop pendulous accelerometer designs vary with different kinds of materials and sensitivities of the core three elements.[13] Until the 1990s, most accelerometers were produced using other than micromachined techniques.

The following Web sites show examples of these techniques:

http://www.humphreyinc.com/la45.htm

http://www.columbiaresearchlab.com/Force2.htm

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13 Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-15. LINEAR ACCELEROMETERS (INCLUDING MEMS ACCELEROMETERS)

Critical Technology Parameter	Any MEMS accelerometer (also known as the "silicon accelerometer") having the following characteristics: 1. Bias stability of less (better) than 130 μg with respect to a fixed calibration value over a period of 1 month; or 2. Scale factor stability of less (better) than 130 ppm with respect to a fixed calibration value over a period of 1 month; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment. Accelerometer axis-alignment stations. The fabrication process relies on commonly available semi-conductor process equipment, including high-precision lithography, ion-milling, plasma-arc, and electronic-sputtering production equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Safety air bags and dynamic vehicle control.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

The microelectronics field has made pure single-crystal silicon readily available, and silicon has excellent mechanical properties: (1) harder than most metals, (2) higher elastic limits in both tension and compression than steel, and (3) negligibly small hysteresis and virtually infinite fatigue life. By using anistropic-etching process, it can be made into microscopically small devices, including accelerometers.

There are many designs of silicon accelerometers, from a simple pendulum to a tuning fork. There are numerous other types. This is a relatively new technology area. MEMS sensors are one-tenth the cost of the electromechanical sensors they replace. This reduced cost will dramatically change the inertial sensor business, just as integrated circuits changed electronics.[14]

The following is a list of associated references or useful Web sites:

J.B. Angell et al., "Silicon Micromechanical Devices," *Scientific American,* pp. 44–45, April 1983.

Anthony Lawrence, *Modern Inertial Technology*, 1998.

Dr. G.T. Schmidt, Draper Lab., *GPS/INS Technology Trends for Military Systems*, 1997.

http://www.base-usa.com/sensor/c3a-02.htm

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[14] Anthony Lawrence, *Modern Inertial Technology,* 1998.

MCTL DATA SHEET 16.1-16. ANGULAR OR ROTATIONAL ACCELEROMETERS

Critical Technology Parameter	Any angular or rotational accelerometer having a drift-rate stability, when measured in a 1-g environment over a period of 10 days and with respect to a fixed calibration value, of 1. Less (better) than 0.01 deg/hr when capable of functioning at linear-acceleration levels below 10 g; or 2. Less (better) than 0.5 deg/hr when capable of functioning at linear-acceleration levels from 10 to 100 g inclusive; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment. Gyroscope axis-alignment fixture. The fabrication process relies on commonly available semiconductor manufacturing equipment, including high-precision lithography, ion-milling, plasma-arc, and electronic-sputtering production equipment.
Unique Software	Algorithms and verified data needed to exceed militarily critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Vehicle control and robotics.
Affordability Issues	None identified.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

Gyroscopes typically measure rotation rate, and accelerometers measure acceleration. Gyroscopes also respond to acceleration forces, and accelerometers sometimes respond to rotational forces.

An angular accelerometer (by integrating twice to get rotation rate) can be used instead of a gyroscope; until recently, however, these sensors could not detect very low frequency or steady inputs. At high frequency they measure well, and so are used in autopilot-stabilization systems and in camera systems. But the absence of a low sensing threshold means that they generally cannot be used for navigation. For in situations where a vehicle makes a long, large-radius turn, or worse, starts a very slow roll, the angular acceleration goes unmeasured if it is below the sensor threshold.[15] (Angular acceleration can also be measured with a linear accelerometer that is mounted off the center of rotation of an object.)

With the growth of MEMS, however, it is becoming feasible to use individual linear and angular MEMS accelerometer sensors. Integrating the outputs of these sensors would compensate for the linear sensitivity of the angular sensor to achieve an instrument that is insensitive to linear acceleration and measures only the angular acceleration, even at low frequencies. A single sensor, called the multifunction sensor, is addressed in a separate data sheet.

As a result of recent developments in angular-rate accelerometer technology, accelerometers have achieved capabilities similar to gyroscopes. This has resulted in IEEE proposing a new definition of gyroscopes, from “a

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15 Anthony Lawrence, *Modern Inertial Technology,* 1998.

device using angular momentum (usually of a spinning rotor)" to "an inertial sensor that measures angular rotation with respect to inertial space about its input axis(es). The sensing of such motion could utilize the angular momentum of a spinning rotor, the Coriolis effect on a vibrating mass, or the Sagnac effect on counter-propagating light beams in a ring laser or an optical fiber coil."

Many manufacturers are developing MEMS accelerometers and gyroscopes, which will reduce the cost of these sensors.

The following is a list of associated references:

"Tiny Inertial Sensors Made on Silicon Chips," *Aviation Week and Space Technology,* August 10, 1998.

LtCol B.M. Kaspar, DARPA, "The DARPA MEMS Inertial Navigation System Program," undated.

Anthony Lawrence, *Modern Inertial Technology,* 1998.

Dr. G.T. Schmidt, Draper Lab., *GPS/INS Technology Trends for Military Systems,* 1997.

The following Web site discusses how accelerometers can replace gyroscopes:

http://www.canova-engineering.com/canvkalm.htm

MCTL DATA SHEET 16.1-17. MULTIFUNCTION INERTIAL SENSORS

Critical Technology Parameter	Any multifunction inertial sensor (includes multiaxis accelerometer) that provides both linear and angular rate sensing having the following characteristics: 1. Linear measurement—bias stability of less (better) than 130 μg with respect to a fixed calibration value over a period of 1 month; or a scale factor stability of less (better) than 130 ppm with respect to a fixed calibration value over a period of 1 month; or 2. Angular measurement—an equivalent drift-rate stability of less (better) than 0.01 deg/hr for less than 10 g or a drift-rate stability of less (better) than 0.5 deg/hr for 10 to 100 g; or 3. Capable of functioning at continuous-acceleration levels, including shock, exceeding 100 g on any platform.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed military critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Automotive stability and robotics.
Affordability Issues	Not determined.
Export Control References	WA ML 9; WA Cat 7; MTCR 9; USML VIII, XII; CCL Cat 7.

BACKGROUND

A multisensor is a single sensor that provides three axes of rate and acceleration. Currently, the best applications for this sensor, because of its size, are in the seeker heads and midcourse guidance systems of high dynamic missiles. Multisensors have an angular rate accuracy ranging from 1 to 10 deg/hr; however, this technology is still emerging, and higher performance is expected within the next few years.

The following is a list of associated references or useful Web sites:

Anthony Lawrence, *Modern Inertial Technology,* 1998.

http://www.systems.gec.com/html/mimu.html

SECTION 16.2—GRAVITY METERS AND GRAVITY GRADIOMETERS

Highlights

- Uncompensated gravity disturbances are a large error source for inertial navigation system initialization and subsequent field operation. Evolving gravity models are enabling better inertial navigation system error compensation.
- Use of a worldwide gravity database based on better instrumentation and having greater computer storage and access capabilities, in conjunction with on-board gravity sensors, provides autonomous and continuous updates to inertial navigation systems, yielding accuracy or noise level comparable with projected inertial navigation system/GPS hybrid systems for short periods of time.
- Gravity meter and gravity gradiometer arrays with accurate time sequencing, faster computer speeds, and memory advances can provide improved detection and location of submarines, mines, tunnels, and mobile missile launchers.
- An evolving technology to compute real-time gravity data from a moving research platform using the difference in acceleration data from an uncompensated inertial navigation system and the GNSS has been demonstrated.
- Another way of computing gravity, using multiple satellites, has great potential of improving Earth-related science.

OVERVIEW

This section of PNT on gravity sensors includes both gravity meters and gravity gradiometers used in either static or moving-base measurements. Every object has a distinctive gravity signature embedded in the spectrum reflected or emitted from it. These sensors can be used for detection of differing masses and for generating a worldwide gravity database that can then be used for navigation-system error compensation. Refer to Inertial Navigation Systems, Section 16.1, and to DBRN, Section 16.3, for moving-base measurements. Compensation techniques must be used to remove the noise caused by the motion (acceleration) of the system and the noise of the mass of the compensation instrumentation. This generally requires a stable reference that can be obtained using gyros. The accuracy or noise level of the system is a function of the system stability and the complexity of the mechanical, electronic, and software compensation systems.

The use of gravity sensors for geodetic measurements and detection is a dual-use application. International cooperative efforts through the International Association of Geodesy (IAG)[16] exist for comparing absolute gravity standards. Many countries have national gravity programs for national and international geoscience requirements. For more information on land and marine gravity methods, see http://www.ngdc.noaa.gov/seg/potfld/gravity; for gravity methods, see http://britannica.com/bcom/eb/article/3/0,5716,120713+6+111024,00.html. Most gravity meters are relative measuring instruments of various types, including La Coste-Romberg and Wordon gravimeters. A gradiometer in principle is immune to the effects of vertical acceleration of the platform and the velocity-dependent interactions with the rotation of Earth.

BACKGROUND

There are several methods of measuring or computing gravity. For instance, an absolute measurement of gravity can be made using accurate timing of a falling weight or a swinging pendulum in a controlled environment;

[16] http://www.gfy.ku.dk/~iag/

a relative gravity measurement can be accomplished by using a gravity meter (gravimeter) or multiple-formation flying satellites. These instruments have parametric outputs expressed in microgals. All these instruments have parametric outputs of the acceleration of gravity called a Galileo (gal), where a gal is equal to 1 cm/sec^2.

All modern gravity meters measure the gravity component along the system axis. The gravity field, g, is a measurement of the tendency of an object to fall in the direction of the gravity vector. That is, it is the acceleration experienced by a body in the absence of other forces. Measurements of the gravity field provide data about the distribution of an attracting mass. Gravity meters are very sensitive instruments that are difficult to build and calibrate; however, they are capable of measuring fractions of Earth's gravity field to a high degree of accuracy. Some instruments can measure to an accuracy of one part per billion of Earth's gravity field.

In its simplest form, a gradiometer is a set of gravimeters separated by a fixed distance, where the gradient is the difference in field values sensed by the gravimeters. The derivative of g is the gradient of gravity. The partial spatial derivatives of the gravity vector yield the gravity gradient tensor, consisting of nine elements. The gravity vector has three spatial components (x, y, and z), and derivatives are taken with respect to each of the spatial directions (x, y, and z) to yield the nine components of the tensor. The gravity gradient tensor (T) is symmetric about its diagonal, so only six of the nine terms (Txx, Tyy, Tzz, Txy, Txz, Tyz) have to be specified. Likewise, satellites separated by a fixed distance tend to separate because of gravity. The signal required to maintain the fixed distance is a function of gravity and other relatively minor perturbations.

Gravity gradiometers measure these gradients of gravity with power spectral density in noise level units of Eötvös[17] squared per radian per second. Further information on Roland von Eötvös can be found at http://www.gfy.ku.dk/~iag/HB2000/part1/historic.htm. The measurement of the gravity gradient tensor is required because of the complications of signal detection when the sensor is moving relative to, and in the complicated gravity field composed of, relative varying density anomalies. To further complicate the problem for the potential field, the direction of the measurements relative to Earth is critical. This requires a stable platform, such as furnished by an inertial navigation system. The gravity gradient can be measured horizontally or vertically relative to Earth's surface or its magnetic field. The horizontal vector of the gravity gradient components points in the direction of increasing gravity (i.e., in the direction of increasing mass). To further complicate the issue, there are both static and mobile gravity meters and gravity gradiometers. More costly static gravity gradiometers are used in lieu of static gravity meters because of their greater resolution, ability to measure multiple gravity vector components (Txx, Tyy, Tzz, Txy, Txz, Tyz), and better signal-to-noise ratio.

The advantage of a moving or dynamic gravity gradiometer is detection of mass differences over a wide area. For a more complete description of gravity and gravity anomalies see *Applied Geophysics,* Second Edition, by Telford, Gelhart, and Sheriff, Cambridge University Press, 1990. Gravity gradiometers can be used to measure a body's gravity field (such as Earth's), which in turn has applications for detection and localization of mass distributions, covert position determination, and inertial navigation system compensation.

Present aircraft and ship inertial navigation systems use coarse models of Earth's gravity to correct for the sensed acceleration of gravity by the system sensors. Gravity anomalies that are not modeled are a major error source and limit the dynamic performance of deployed inertial navigation systems. Precision inertial navigation system navigation is currently limited by gravity anomalies. A synergistic effect results from an inertial navigation system measuring acceleration and a gravity gradiometer measuring local gravity. The inertial navigation system measures an acceleration that includes the effects of local gravity, which need to be eliminated to accurately determine the true acceleration, velocity, and distance traveled of the vehicle. The gravity gradiometer requires accurate attitude from the inertial navigation system to stabilize the sensor. If a gravity gradiometer could be produced at comparable cost to the ring laser gyroscope or fiber-optic gyroscope, there would be widespread acceptance of the technology, and the hybrid market would be substantial. The strategic importance of high accuracy, low noise level, low-cost gravity sensors should not be understated. The country which is capable of hybridizing gravity sensors and inertial

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17 The units of gradient, Eötvös unit (EU), are named after Roland von Eötvös. 1 EU = 10^{-6} milligal/cm; a gal is equal to 1 cm/sec^2. The URL http://www.gfy.ku.dk/~iag/HB2000/part1/historic.htm has further information on Roland von Eötvös. In the text, Eötvös is used as the unit of measure.

navigation systems will be able to operate without GPS at near-GPS levels of position accuracy for short time periods.

LIST OF MCTL TECHNOLOGY DATA SHEETS
16.2. GRAVITY METERS AND GRAVITY GRADIOMETERS

MCTL DATA SHEET 16.2-1. GRAVITY METERS (GRAVIMETERS) FOR STATIC MEASUREMENTS

Critical Technology Parameter	Any gravity meter (gravimeter) capable of static operation that has an accuracy of less (better) than 10 μgal.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, or alignment equipment to calibrate gravimeters with a static accuracy of less (better) than 10 μgal. Accelerometer axis-alignment stations.
Unique Software	Verified data for gravity surveys and algorithms to be used for real-time gravity compensation.
Major Commercial Applications	Geodetic mapping, resource exploration, and mass detection.
Affordability Issues	Highly specialized sensor system with minimum, but critical, applications.
Export Control References	WA ML 5, 9; WA Cat 6; MTCR 12; CCL Cat 6.

BACKGROUND

There are two methods of measuring gravity. An absolute measurement of gravity can be made using accurate timing of a falling weight or a swinging pendulum in a controlled environment. Relative gravity measurements may be made in various ways. Three types of relative gravity instruments—the torsion balance, the pendulum, and the gravity meter (or gravimeter)—have been used. All these instruments have parametric outputs of the acceleration of gravity called a Galileo (gal), where a gal is equal to 1 cm/sec^2.

Gravity meters can be used in a static or dynamic (moving) base to measure the magnitude acceleration of gravity. In a static environment, a gravity meter is capable of measuring Earth's gravity to a greater degree of accuracy than the dynamic (moving) gravity meter, which suffers from acceleration noise due to motion. For the latter, more electronics, software, and gyro stabilization may be required to compensate for the motion effects to gravity.

The following is a list of associated references or useful Web sites:

W.M. Telford et al., *Applied Geophysics,* 1990.

http://www.lacosteromberg.com/gravitymeters.htm (gravity meter)

http://www.lacosteromberg.com/gravitymeters.htm (gravity meter)

http://www.geotools.com/ (links to sensors/products/services)

MCTL DATA SHEET 16.2-2. GRAVITY METERS (GRAVIMETERS) FOR MOVING-BASE MEASUREMENTS

Critical Technology Parameter	Any gravity meter (gravimeter) capable of mobile operation that has an accuracy of less (better) than 0.7 milligal with a time-to-steady-state registration of less (better) than 2 min under any combination of attendant corrective compensation and motional influences.
Critical Materials	Beryllium.
Unique Test, Production, Inspection Equipment	Test, calibration, modeling, compensation, or alignment equipment necessary to obtain mobile accuracy of less (better) than 0.1 milligal. Accelerometer axis-alignment stations.
Unique Software	Verified data from gravity surveys and algorithms to be used for real-time gravity compensation or arrays. Specially designed software to correct motional influences.
Major Commercial Applications	Geologic mapping and resource exploration.
Affordability Issues	Cost is proportional to usage. This is not a high-volume production technology, but rather a highly specialized sensor system with minimum, but critical, applications.
Export Control References	WA ML 9; WA Cat 6; MTCR 12; CCL Cat 6.

BACKGROUND

There are two methods of measuring gravity. An absolute measurement of gravity can be made using accurate timing of a falling weight or a swinging pendulum in a controlled environment. Relative gravity measurements may be made in various ways. Three types of relative-gravity instruments—the torsion balance, the pendulum, and the gravity meter (or gravimeter)—have been used. All these instruments have parametric outputs of the acceleration of gravity called a Galileo (gal), where a gal is equal to 1 cm/sec^2. The use of accuracy in milligals reflects a desire to standardize.

Gravity meters can be used in a static or dynamic (moving) base to measure variations in the gravitational field of Earth by detecting differences in weight of an object of constant mass at different points on Earth's surface. In a static environment, a gravity meter is capable of measuring Earth's gravity to a greater degree of accuracy than the dynamic (moving) gravity meter, which suffers from acceleration noise due to motion. For moving-base measurements, compensation techniques must be used to remove the noise caused by the motion (acceleration) of the system and the noise of the mass of the compensation instrumentation. This generally requires a stable reference that can be obtained using gyros. The accuracy or noise level of the system is a function of the stability of the system and the complexity of the mechanical, electronic, and software-compensation systems.

The following is a list of associated references or useful Web sites:

W.M. Telford et al., *Applied Geophysics*, 1990.

http://www.pd.uwa.edu.au/~frank/NewScientist/gravity.html (navigating with gravity)

http://www.geotools.com/ (links to gravity sources)

http://www.lacosteromberg.com/modelefr.htm (description of a commercial portable gravity meter)

http://www.lacosteromberg.com/gravitymeters.htm (gravity meter-moving)

MCTL DATA SHEET 16.2-3. GRAVITY GRADIOMETERS FOR STATIC MEASUREMENTS

Critical Technology Parameter	Any gravity gradiometer capable of operation on a static platform with a noise level of less (better) than 1.0 Eötvös squared per radian per second.
Critical Materials	Beryllium.
Unique Test, Production, Inspection Equipment	Test calibration, modeling, compensation or alignment equipment to obtain static noise level of less (better) than 1.0 Eötvös squared per radian per second. Accelerometer axis-alignment stations.
Unique Software	Interpretation software. Verified data from gravity static surveys and algorithms to be used for real-time gravity compensation.
Major Commercial Applications	Geologic mapping and resource exploration. Cargo detection and weight in motion. Oil production enhancement. Tunnel detection
Affordability Issues	Cost is proportional to usage. This is not a high-volume production technology, but a highly specialized sensor system with minimum, but critical, applications.
Export Control References	WA ML 5, 9; WA Cat 6; MTCR 12; CCL Cat 6.

BACKGROUND

A gradiometer can be thought of as an assemblage of gravity meters with some spatial separation. The difference between readings reflects the rate of change of gravity along the direction in which the meters are separated. Over the past 50 years, a single gravity meter alternately placed at two positions on a tower would measure the vertical component of the vertical gravity field. Similar measurements can be achieved for the horizontal gradients of gravity. In 1886, Baron von Eötvös introduced an instrument in which two weights were suspended from a torsion fiber at unequal heights. The weights, separated both vertically and horizontally, experienced different forces due to both spatial separations.

The gradients, the second partial derivatives of the gravity potential, W, constitute the elements of *Eötvös tensor* (or gravity gradient tensor). The derivative of g is the gradient of gravity. In its simplest form, a gradiometer is a set of gravimeters separated by a fixed distance, where the gradient is the difference in field values sensed by the gravimeters. The partial spatial derivatives of the gravity vector yield the gravity gradient tensor, which consists of nine elements. The gravity vector has three spatial components (x, y, and z), and derivatives are taken with respect to each of the spatial directions (x, y, and z) to yield the nine components of the tensor. The gravity gradient tensor (T) is symmetric about its diagonal, so only six of the nine terms (Txx, Tyy, Tzz, Txy, Txz, Tyz) have to be specified. The more costly static gradiometer is used in lieu of a gravity meter because of its greater resolution, ability to measure multiple gravity vector components (Txx, Tyy, Tzz, Txy, Txz, Tyz), and better signal-to-noise ratio.

The following is a list of associated or useful Web sites:

W.M. Telford et al., *Applied Geophysics*, 1990.

Richard Hansen et al., "The Leading Edge," in *The Gravity Gradiometer: Basic Concepts and Tradeoffs*, April 1999.

http://www.pd.uwa.edu.au/~frank/NewScientist/gravity.html (seeing with gravity)

http://www.geotools.com/ (links to gravity sources)

http://features.learningkingdom.com/fact/archive/1998/11/11.html

http://es.epa.gov/ncerqa_abstracts/sbir/other/monana/warburto.html (superconducting gravity gradiometer)

MCTL DATA SHEET 16.2-4. GRAVITY GRADIOMETERS FOR MOVING-BASE MEASUREMENTS

Critical Technology Parameter	Any gravity gradiometer capable of operation on a moving platform with a noise level of less (better) than 300 Eötvös squared per radian per second.
Critical Materials	Beryllium.
Unique Test, Production, Inspection Equipment	Test calibration, modeling, compensation or alignment equipment necessary to obtain mobile noise level of less (better) than 300 Eötvös squared per radian per second. Accelerometer axis-alignment stations.
Unique Software	Algorithms for compensation of environmental effects, map matching, interpretation, terrain estimation, and other unique military applications. Verified data from gravity surveys and algorithms for real-time gravity compensation.
Major Commercial Applications	Geologic mapping and resource exploration. Mass detection, cargo detection, tunnel detection, and weigh in motion.
Affordability Issues	This is a highly specialized sensor system, produced in low volume, and as a result, expensive. The size of the market does not justify modification of the technology to reduce cost. If low-cost accelerometer accuracy can be dramatically improved, the military utility of gravity gradiometer arrays will increase.
Export Control References	WA ML 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

A gradiometer can be thought of as an assemblage of gravity meters with some spatial separation. The difference between readings reflects the rate of change of gravity along the direction in which the meters are separated. Over the past 50 years, a single gravity meter alternately placed at two positions on a tower would measure the vertical component of the vertical gravity field. Similar measurements can be achieved for the horizontal gradients of gravity. In 1886 Baron von Eötvös announced an instrument in which two weights were suspended from a torsion fiber at unequal heights. Because the weights were separated both vertically and horizontally, they experienced different forces due to both spatial separations.

The gradients, the second partial derivatives of the gravity potential W, constitute the elements of *Eötvös tensor* (or gravity gradient tensor). The derivative of g is the gradient of gravity. In its simplest form, a gradiometer is a set of gravimeters separated by a fixed distance, where the gradient is the difference in field values sensed by the gravimeters. The partial spatial derivatives of the gravity vector yield the gravity gradient tensor consisting of nine elements. The gravity vector has three spatial components (x, y, and z) and derivatives are taken with respect to each of the spatial directions (x, y, and z) to yield the nine components of the tensor. The gravity gradient tensor (T) is symmetric about its diagonal, so only six of the nine terms (Txx, Tyy, Tzz, Txy, Txz, Tyz) have to be specified. For moving-base measurements, compensation techniques must be used to remove the noise caused by the motion (acceleration) of the system and the noise of the mass of the compensation instrumentation. This generally requires a stable reference that can be obtained using gyros. The accuracy or noise level of the system is a function of the stability of the system and the complexity of the mechanical, electronic, and software-compensation systems.

The following is a list of associated references or useful Web sites:

W.M. Telford et al., *Applied Geophysics*, 1990.

Aviation Week and Space Technology, March 4, 2002, pg. 58.

Richard Hansen et al., "The Leading Edge," in *The Gravity Gradiometer: Basic Concepts and Tradeoffs*, April 1999.

http://www.pd.uwa.edu.au/~frank/NewScientist/gravity.html (*Seeing with Gravity*)

http://www.geotools.com/ (links to gravity sources)

http://features.learningkingdom.com/fact/archive/1998/11/11.html

http://www.pd.uwa.edu.au/Physics/Research/instruments.html (cryogenic gravity gradiometer moving)

http://es.epa.gov/ncerqa_abstracts/sbir/other/monana/warburto.html (superconducting gravity gradiometer)

http://cryowwwebber.gsfc.nasa.gov/other_hardware/SGG/SGG.html (superconducting gravity gradiometer)

SECTION 16.3—RATIO AND DATA-BASED REFERENCED NAVIGATION SYSTEMS

Highlights

- GPS remains the predominant worldwide standard for PNT dissemination. Interoperability with Galileo is critical.
- POSITIME technology improves combat situational awareness by providing real-time knowledge of the location and movement of allied and enemy forces.
- Over the past 4 years, there has been a GPS receiver technology and application explosion, primarily driven by the commercial markets and new electronic technologies. This has resulted in significant cost and size reduction of GPS receivers, increasing the ratio of commercial to military users dramatically. The GPS is undergoing a modernization effort to improve performance in times of conflict and of peace.
- International GNSS (GLONASS and the proposed European Union Galileo) capabilities will continue to be developed as alternatives to GPS and as a means of providing independence, better redundancy, and integrity monitoring.
- An updated LORAN can be used as a backup to GPS for PT&F dissemination and large-area coverage for positioning.
- Hybrid GNSS (GPS, GLONASS) with DGPS, LORAN, Doppler systems, JTIDS, EPLRS, and DBRN will minimize the impact of GPS signal loss and jamming. GPS is undergoing a modernization program to improve antijam, accuracy, and security features.
- The recent Shuttle Radar Topography Mission that mapped over 80 percent of Earth, along with continued improvements to computer speed and memory and the orbiting gravity mapper programs such as GRACE, will significantly improve DBRN technology.
- LPI/LPD radar altimeters integrated with terrain databases provide a military alternative to GPS navigation, particularly in a jamming environment.

OVERVIEW

This section of PNT covers a limited category of militarily critical radio and DBRN technologies and systems having a wide range of dual-use applications. The U.S. GNSS, called GPS, consists of three segments: (1) space systems (including satellites), (2) ground-control systems, and (3) user receivers and associated equipment. Only the last is included in this section [refer to Section 19 for (1) and (2)]. GPS also provides PT&F for military telecommunications and navigation.

Critical radio systems include differential GNSS (DGNSS) receivers and hybrid radio navigation receivers using GPS, GLONASS, Galileo, LORAN, Doppler, altitude measurement, or DBRN. Other systems include (1) JTIDS—the U.S. military's principal tactical platform communication link and relative navigation capability and (2) Enhanced Position Location Reporting System (EPLRS). The DBRN technology provides an autonomous, covert hybridization using 3–D digital-terrain maps and other geomapping databases or bathymetric, stellar, gravity, and magnetic databases that have proliferation concerns. Three-dimensional position ambiguities and other properties, such as magnetic and gravity signatures, can be resolved and optimized as stored geodetic data for navigation reference using sensors such as astro-trackers, radar altimeters, magnetometers, gravity meters, and acoustic sensors. For gravity and magnetic field databases, see Sections 16.2 and 16.4, respectively. LORAN can also provide timing and frequency information. For mobile users and much of the populated world, the option to use LORAN for critical redundancy of accurate time dissemination is being pursued (refer to Section 16.5 for PT&F

technologies and systems). For hybrid GPS/inertial navigation systems, refer to Section 16.1. Other technologies included in this section are LPI/LPD Doppler/sonar navigation systems and radar altimeters/fathometers, as well as radio direction-finding equipment.

The 2001 Federal Radionavigation Plan[18] specifies civil radio navigation applications.

BACKGROUND

GPS is the current worldwide standard for PNT dissemination, and below we list key historical GPS events and their impact on other radio navigation systems. Included are events that had a significant impact on the movement of the GPS from a unique military capability to a worldwide standard.

Key GPS Historical Events[19]

1959 TRANSIT, the first operational satellite-based navigation system, is developed by John Hopkins Applied Physics Laboratory. The system was originally intended to support the U.S. Navy's submarine fleet.

1964 Timation, a Navy satellite system, is developed at the NRL for advancing the development of high-stability clocks, time-transfer capability, and 2–D navigation. The first Timation satellite is launched in May 1967.

1973 DoD determines need for a joint tri-Service program, consolidating various concepts into a single comprehensive system known as the Defense Navigation Satellite System (DNSS). The new system is to be developed by a Joint Program Office (JPO). The first DNSS (now called NAVSTAR) is launched in 1974.

1983 Following the Soviet downing of Korean Air Flight 007, President Reagan offers to make GPS (previously NAVSTAR) available for use by civilian aircraft. This marks the beginning of the spread of GPS technology from military to civilian aircraft.

1990 DoD activates S/A, the purposeful degradation in GPS navigation accuracy, to no less than 100 m for non-DoD users.

1991 The United States revises export regulations, making a clear delineation between military and civil GPS receivers.

1992 The United States offers to make GPS available to international community. President Clinton reaffirms this in 1995.

1993 The Secretary of Defense formally declares initial operational capability of GPS. No longer a developmental system, GPS is capable of sustaining the 100-m accuracy and continuous worldwide availability.

1994 The Federal Aviation Administration (FAA) approves GPS for use as a stand-alone navigation aid for all phases of flight through nonprecision approach. The FAA also announces the implementation of the Wide-Area Augmentation System (WAAS) for the improvement of GPS integrity and availability for civil users in all phases of flight.

1995 DoD declares full operational capability of GPS. International Civil Aviation Organization (ICAO) endorses the GNSS as the core system for international use and cancels the requirement for Microwave Landing System.

1996 President Clinton signs Presidential Directive NSTC–6, which states intention to discontinue use of S/A by 2006.

1997 Omega ceases operation as a navigation, positioning, and timing system on 30 September.

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[18] DOT-VNTS-RSPA-01-3, DOD-4650.5, pg. 2-30 to 2-32, 3–5
http://www.navcen.uscg.gov/pubs/FRP2001/FRP2001.pdf

[19] Scott Pace et al., "The Global Positioning System, Assessing National Policies," RAND Corporation, 1995.

1999 The Federal Radionavigation Plan removes firm date for demise of LORAN. The recently formed Interagency GPS Executive Board (IGEB) prepares national GPS plan to support global PNT services to users through an optimized system architecture consisting of GPS and augmentations to GPS.

2000 President Clinton announces the discontinuance of GPS S/A effective midnight 1 May 2000.

LIST OF MCTL TECHNOLOGY DATA SHEETS
16.3. RADIO AND DATA-BASED REFERENCED NAVIGATION SYSTEMS

MCTL DATA SHEET 16.3-1. GLOBAL NAVIGATION SATELLITE SYSTEM RECEIVERS

Critical Technology Parameter	Any GNSS receiver equipment that has the following characteristics: 1. Uses military cryptographic modules, integrated circuits, or components of software designed for generating the GPS Y-code and M-code signals for the purpose of information security and key management; uses active and passive antijam systems with the ability to respond to incoming interference (null steering antenna) or generate a high-gain beam toward the GPS satellite, or uses suppression technology to reduce jamming signals; is designed or modified for use with active and passive countermeasures and counter-countermeasures; or has encrypted GPS/ transponder integration capability; or 2. Is designed for producing navigation results above altitudes exceeding 60,000 ft and velocity at or exceeding 1,000 knots; or 3. Is designed or modified for use with unmanned vehicles.
Critical Materials	Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic.
Unique Test, Production, Inspection Equipment	Systems that simulate or generate the specialized radio frequency signal and data message structure and require the use of U.S. cryptography. Antispoofing signal simulators with less (better) than 28 ns measurement capability; electronic counter-countermeasures (ECCM) or interference resistance receivers.
Unique Software	Algorithms that contain U.S. cryptographic logic and other signal-protection and signal-prevention techniques. Controls for input/output ports that transfer classified national-security information.
Major Commercial Applications	Ground-vehicle navigation, aircraft navigation, space-vehicle navigation, and surveying. DoD has exclusive access to corrected U.S. GPS pseudorange, delta range, and ephemeris data.
Affordability Issues	Accuracy and autonomy are the key drivers. Reduced processor costs and memory will significantly reduce costs.
Export Control References	WA ML 9; WA Cat 7; MTCR 11; USML XV; CCL Cat 7.

BACKGROUND

GNSS are satellite-based radio navigation systems that enable an unlimited number of users to do all-weather 3–D positioning, velocity measuring, and timing anywhere in the world or near-Earth space. Currently, the only two GNSS are the U.S. GPS and Russia's GLONASS. For more information on GLONASS refer to http://www.rssi.ru/SFCSIC/english.html

A constellation of 24 satellites acts as reference points from which GPS receivers on the ground "triangulate" their position. By measuring the travel time of signals transmitted from the satellites, a GPS receiver on the ground can determine its distance from each satellite. And with distance measurements from at least four different satellites and some high-powered math, the receiver can calculate its position, altitude, course, and speed.[20]

[20] *Differential GPS Explained,* Trimble, 1993.

The following is a list of associated references or useful Web sites:

Federal Radionavigation Plan, http://www.NAVCEN.uscg.gov/pubs/FRP2001/FRP2001.pdf

http://www.peterson.af.mil/usspace/gps_support/sps_signal_spec.htm (DoD GPS SPS signal specification).

The Global Positioning System: Assessing National Policies, RAND, 1995.

Aerospace Source Book 2000, Aviation Week & Space Technology, January 17, 2001.

http://www.gislinx.com/

http://www.gpsworld.com/gpsworld/article/articleDetail.jsp?id=13014

http://www.rssi.ru/SFCSIC/int.txt

MCTL DATA SHEET 16.3-2. MULTICHIP MODULE) TECHNOLOGY (GPS RECEIVER ON A CHIP)

Critical Technology Parameter	Any multichip GNSS receiver equipment that has the following characteristics: 1. Uses military cryptographic modules, integrated circuits, or components of software designed for generating the GPS Y-code and M-code signals for the purpose of information security and key management; uses active and passive antijam systems with the ability to respond to incoming interference (null steering antenna) or generate a high-gain beam toward the GPS satellite, or uses suppression technology to reduce jamming signals; is designed or modified for use with active and passive countermeasures and counter-countermeasures; or has encrypted GPS/transponder integration capability; or 2. Is designed for producing navigation results above altitudes exceeding 60,000 ft and velocity at or exceeding 1,000 knots; or 3. Is designed or modified for use with unmanned vehicles.
Critical Materials	Matched substrate material thermoconductivity, heat transfer, and strength. Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic.
Unique Test, Production, Inspection Equipment	Systems that simulate or generate the specialized radio-frequency signal and data message structure and require the use of U.S. cryptography. Antispoofing signal simulators with less (better) than 28 ns measurement capability; ECCM or interference resistance receivers.
Unique Software	Computer-aided engineering (CAE) and automatic terrain following (ATF) software for multichip-module design and development. Spread-spectrum technology. Encrypted algorithms and verified data. Algorithms that contain U.S. cryptographic logic and other signal-protection and signal-prevention techniques. Controls for input/output ports that transfer classified national security information.
Major Commercial Applications	Commercial land, aviation, and maritime navigation. Cellular phone location and child locator system.
Affordability Issues	Reduced size and increased commercialization will significantly reduce cost.
Export Control References	WA ML 9; WA Cat 3, 7; MTCR 11; USML XV; CCL Cat 7.

BACKGROUND

Through the use of advanced, high-density radio frequency and multichip-module technology, it is currently possible to fabricate a "GPS Receiver on a Chip."

The largest market driving this technology is wireless communications. The FCC has mandated that all cellular phones identify their location to within 125 m for 911 emergency calls. On 1 May 2000, President Clinton discontinued GPS S/A. With S/A discontinued, the former 100 m, 95-percent accuracy value for the SPS users was replaced by two specification values: 25 m, 95 percent, for when the ionosphere delay-term model errors are large, and 14 m, 95 percent, for when the ionosphere delay-term model errors are small. The enhanced 911 mandate took effect in October 2001.

MCTL DATA SHEET 16.3-3. DIFFERENTIAL GLOBAL NAVIGATION SATELLITE SYSTEM RECEIVERS

Critical Technology Parameter	Any DGNSS receiver equipment that has the following characteristics: 1. Uses military cryptographic modules, integrated circuits, or components of software designed for generating the GPS Y-code and M-code signals for the purpose of information security and key management; uses active and passive antijam systems with the ability to respond to incoming interference (null steering antenna) or generate a high-gain beam toward the GPS satellite, or uses suppression technology to reduce jamming signals; is designed or modified for use with active and passive countermeasures and counter-countermeasures; or has encrypted GPS/ transponder integration capability; or 2. Is designed for producing navigation results above altitudes exceeding 60,000 feet and velocity at or exceeding 1,000 knots; or 3. Is designed or modified for use with unmanned vehicles.
Critical Materials	Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic.
Unique Test, Production, Inspection Equipment	Systems that simulate/generate the specialized radio-frequency signal and data message structure and require the use of U.S. cryptography. Antispoofing signal simulators with less (better) than 28 ns measurement capability.
Unique Software	DGNSS algorithms that contain U.S. cryptographic logic and other signal-protection and signal-prevention techniques. Controls of input/output ports that transfer classified national security information. DGNSS algorithms may contain U.S. cryptographic logic to accommodate the protection scheme of an encrypted DGPS data link.
Major Commercial Applications	Ground-vehicle navigation, aircraft navigation, and surveying.
Affordability Issues	Accuracy and autonomy are the key cost drivers.
Export Control References	WA ML 9; WA Cat 7; MTCR 11; USML XV; CCL Cat 7.

BACKGROUND

Normally, a DGNSS uses a small ground station outfitted with a GPS receiver, the geographic location of which is precisely determined. The timing error of each satellite's contribution to the error between the surveyed and the GPS position is transmitted to another user over a different frequency. The differential station can be mobile on Earth's surface, airborne, or in space. The position of the ground or airborne station can also be transmitted at a frequency different from that used by GPS or at a GPS frequency. When using surveyed positions for the station, this procedure can provide an accuracy of much better than 1 m. DGNSS or DGPS stations are nothing more than pseudolites that give users another source of timing and positioning data. An extension of the total navigation concept is to have a ranging ability among military and civilian users. As the members of the community range on each other and share their known positional and velocity-vector information, the community's total information can be used to improve the positional and velocity-vector accuracy of each member in the community. This accuracy improves as the length of time that each member is in the community increases. Not all members need to transmit to belong to the community, and the information can be encrypted for military users. Each member of the community may or may not have the same set of navigational equipment beyond the radio equipment. This could include inertial navigation systems, LORAN, celestial (stellar), radar, DBRN, etc. The weighting factor of each member's contribution to the total accuracy of the community is determined by the accuracy capability of the navigation system on each platform. This is particularly important in an urban environment, where normal GPS signals may not be received. In fact, a member of the community could be a soldier equipped with radio equipment that allows him to receive these signals covertly despite the urban environment blockage and noise. Other members of the community could be equipped with LPI/LPD radio equipment.

On 1 May 2000, S/A was discontinued in the GPS satellites. Even with S/A discontinued, the need to use DGPS corrections and develop systems that produce the correction data continues. RTCM SC–104, the U.S. maritime DGPS standard, which has essentially been adopted worldwide, has the capability to generate corrections for GLONASS as well as for GPS. The U.S. Coast Guard never implemented the GLONASS corrections, even though this is an accepted method of implementing the RTCM standard.

The following is a list of associated references or useful Web sites:

Federal Radionavigation Plan, http://www.NAVCEN.uscg.gov/pubs/FRP2001/FRP2001.pdf

J. Hurn, *Differential GPS Explained*, 1993.

http://www.gpsworld.com/gpsworld/article/articleDetail.jsp?id=13014

http://www.rssi.ru/SFCSIC/13.txt (DGLONASS in Russia)

http://www.navcen.uscg.gov/dgps/Default.htm

http://www.sdd.sri.com/DGPS/edge.html

MCTL DATA SHEET 16.3-4. HYBRID[21] RADIO AND DATA-BASED REFERENCED NAVIGATION SYSTEMS (OTHER THAN INERTIAL NAVIGATION SYSTEMS)

Critical Technology Parameter	Any hybrid GNSS/radio navigation system or DBRN receiver equipment that has the following characteristics: 1. Position accuracy, without GNSS or after loss of GNSS for a period of up to 4 min, of less (better) than 10 m CEP; or 2. Interfaces with a military GNSS that has the following characteristics: a. Uses military cryptographic modules, integrated circuits, or components of software designed for generating the GPS Y-code signal for the purpose of information security and key management; uses active and passive antijam systems with the ability to respond to incoming interference (null steering antenna) or generate a high-gain beam towards the GPS satellite, or uses suppression technology to reduce jamming signals; is designed or modified for use with active and passive countermeasures and counter-counter-measures; or has encrypted GPS/Transponder integration capability; or b. Has input/output interface that accommodates the transfer of local and wide-area DGPS corrections to improve accuracy and integrity; or c. Is designed for producing navigation results above altitudes exceeding 60,000 ft and velocity exceeding 1,000 knots; or d. Is designed or modified for use with unmanned vehicles; or e. Is designed or modified for covert determination of position or velocity. **Note: For hybrid inertial navigation systems/GNSS or DBRN equipment refer to Section 16.1.**
Critical Materials	Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment. GNSS receivers requiring special simulator testing systems. Specially designed test, calibration, or alignment equipment. Antispoofing and signal simulators with less (better) than 28 ns measurement capability; ECCM or interference resistance receivers.
Unique Software	Source code, algorithms, and verified data needed to exceed militarily critical parameters with any of the following navigation data: 1. LORAN, Doppler (radar, laser, or sonar), Air Data, or DBRN (bathymetric, stellar, gravity, and magnetic databases, or 3–D digital-terrain maps and other geomapping data), JTIDS, or EPLRS.
Major Commercial Applications	Ground-vehicle navigation, aircraft and space navigation, underwater-vehicle navigation, mining, and farming.
Affordability Issues	Accuracy and autonomy are the key cost drivers.
Export Control References	WA ML 9; WA Cat 7; MTCR 11; USML XV; CCL Cat 7.

[21] The term "integrated" or "hybrid" is the same for this technology.

BACKGROUND

Using data-fusion computing techniques, hybrid radio-navigation systems, such as GNSS (GPS + GLONASS), or any combination of LORAN, Doppler, air data, or DBRN can provide increased positioning accuracy. Hybrid radio navigation also provides a "flywheel" effect for continuous, accurate navigation, even when any one of these other navigation signals is lost.

On 1 May 2000, S/A was discontinued in the GPS satellites. Even with S/A discontinued, the need to use DGPS corrections and develop systems that produce the correction data continues.

The following is a list of associated references or useful Web sites:

Federal Radionavigation Plan, http://www.NAVCEN.uscg.gov/pubs/FRP2001/FRP2001.pdf

B. Peterson et al., *Integrated GPS/LORAN: Structures and Issues,* 1998.

http://www.sdd.sri.com/DGPS/edge.html

http://www.locusinc.com/loran-news.htm

http://www.gpsworld.com/gpsworld/article/articleDetail.jsp?id=13014

MCTL DATA SHEET 16.3-5. DOPPLER (RADAR OR SONAR) NAVIGATION SYSTEMS AND PASSIVE ACOUSTIC NAVIGATION SYSTEMS

Critical Technology Parameter	1. Any Doppler navigation system (radar or sonar) having the following characteristics: a. Power management or using phase-shift-key modulation techniques; or b. Any technique that reduces signal detectability, including antenna steering or beaming technology; or 2. For Doppler radar systems, a scale-factor error of less (better) than 0.5 percent of distance traveled. For Doppler sonar systems, a scale-factor error of less (better) than 1.0 percent of distance traveled. 3. Any acoustic system for determining the position of surface or underwater vehicles having an accuracy less than 10 m (CEP) at ranges greater than 1,000 m.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and source codes that reduce signal detectability, including antenna cross-correlation algorithms and verified data.
Major Commercial Applications	None identified for LPI/LPD technology, but basic Doppler navigation systems have wide applications in commercial aviation, space, land, and sea vehicles, including weather tracking.
Affordability Issues	Military-unique LPI software requirement may drive up cost, unless hardware maximizes commercial technology.
Export Control References	WA ML 9; WA Cat 7; MTCR 11; USML XV; CCL Cat 7.

BACKGROUND

Doppler (radar or sonar) navigation is dead reckoning in that it tracks changes in position from a known starting point. The Doppler velocity sensor determines velocity and drift angle by measuring the Doppler frequency shift (Doppler effect) from narrow radar or sonar beams transmitted at oblique angles from the vehicle toward the ground. For underwater navigation in a localized area, relative position accuracies are achievable within transducers in a network of acoustic transponders providing coordinates of an acoustic grid. For additional information on the Doppler effect, see http://astrosun.tn.cornell.edu/courses/astro201/doppler.htm.

The following is a list of other associated or useful Web sites:

http://www.systems.gec.com/html/an_asn-128_b_doppler_gps_navig.html

http://www.fas.org/man/dod-101/navy/docs/fun/part09.htm

MCTL DATA SHEET 16.3-6. DIRECTION-FINDING EQUIPMENT

Critical Technology Parameter	Any direction-finding equipment having the following characteristics: • Operating at frequencies above 30 MHz (for airborne automatic direction-finding equipment, operating at frequencies exceeding 5 MHz) and having an instantaneous bandwidth of 1 MHz or more and • Having a processing rate of more than 1,000 direction-finding results per second and per frequency channel, or • Having a relative bearing accuracy of better than 0.5 deg LOS from transmitter.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, or alignment equipment specially designed for direction-finding equipment at the above technology parameters.
Unique Software	Source code for the development of this equipment.
Major Commercial Applications	General aviation and police (vehicle and hostage tracking).
Affordability Issues	Not an issue.
Export Control References	WA ML 9; WA Cat 7; MTCR 11; USML XI; CCL Cat 7.

BACKGROUND

Direction-finding equipment determines the direction of a transmitter by means of its emission.

The following is a list of associated or useful Web sites:

http://www.directionfinder.com/rdf.htm

http://www.bsn.ch/contest/valladolid/217.html

http://snoopy.csie.ntu.edu.tw/archive/volume2/217.html

MCTL DATA SHEET 16.3-7. DATA-BASED REFERENCED NAVIGATION SYSTEMS (DIGITAL TERRAIN, BATHYMETRIC, MAGNETIC, GRAVITY, AND STELLAR)

Critical Technology Parameter	Any DBRN system or combination thereof having the following characteristics: 1. Navigation accuracy less (better) than 10 m CEP, or 2. Designed or modified for use in an unmanned vehicle.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Unique computer test models for optimization of database manipulation and extraction.
Unique Software	Algorithms for image correlation and pattern recognition. Integration and data-analysis algorithms and verified data. Source code, algorithms, and verified data needed to exceed militarily critical parameters with any of the following navigation data: stellar or celestial, geo-magnetic, geo-gravity, bathymetric, 3–D digital-terrain maps, and other geomapping data.
Major Commercial Applications	Ground-vehicle navigation, aircraft navigation, ship-channel navigation, farming, and surveying recovery.
Affordability Issues	Lighter and less expensive systems will open more commercial applications.
Export Control References	WA ML 9; WA Cat 7; MTCR 11; USML XI; CCL Cat 7.

BACKGROUND

DBRN systems use various sources of previously measured geomapping data integrated to provide accurate navigation information under dynamic conditions. Data sources include bathymetric maps, stellar maps, gravity maps, magnetic maps, or 3–D digital terrain maps.

The following is a list of associated references or useful Web sites:

Federal Radionavigation Plan, http://www.NAVCEN.uscg.gov/pubs/FRP2001/FRP2001.pdf

http://www.base-usa.com/terpfact.htm

MCTL DATA SHEET 16.3-8. LPI/LPD RADAR ALTIMETERS AND FATHOMETERS

Critical Technology Parameter	Any radar altimeter or fathometer (also called a depth finder) having the following characteristics: 1. Power management or use of phase-shift-key modulation techniques or 2. Any technique that reduces signal detectability, including antenna steering or beaming technology.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and source codes that reduce signal detectability, including antenna cross-correlation algorithms and verified data.
Major Commercial Applications	None identified for LPI/LPD technology, but basic radar altimeter and fathometer systems have wide applications in commercial aviation, space, land, and marine vehicles.
Affordability Issues	Military-unique LPI software requirement may drive up cost, unless hardware maximizes commercial technology.
Export Control References	WA ML 9; WA Cat 7; MTCR 11; USML XV; CCL Cat 7.

BACKGROUND

Radar altimeters provide height-above-terrain, while fathometers provide distance above ocean bottom terrain.

The use of low probability of intercept (LPI) or low probability of detection (LPD) techniques reduces the emitting power of these devices.

The following is a list of associated or useful Web sites:

http://www.gecm.hazeltine.com/html

http://www.systems.gec.com/html/low_probability_of_intercept_a.html

http://www.roke.co.uk/products/altimeter.html

SECTION 16.4—MAGNETIC AND ELECTROMAGNETIC SENSOR SYSTEMS

Highlights

- Magnetic and electromagnetic sensor technology varies greatly with type, application, and cost.
- Magnetic and electromagnetic sensor systems and arrays provide a covert detection and classification technology.
- More use of low-cost, thin-film MR sensors is expected for a number of applications for which cost, size, and power are driving factors, such as mine detection and area security.
- Newly developed potassium and helium-4 (He-4) optically pumped magnetometers are demonstrating performance comparable to SQUID magnetometers at lower cost and without the logistic complication of maintaining superconductive temperatures in a battlespace environment.
- Biomedical research and diagnostics and nondestructive evaluations are major military funding sources for future usage of SQUID sensors.
- Magnetic gradiometers, utilizing either the SQUID or potassium technologies, nearly eliminate the natural geomagnetic background noise.
- High superconducting temperature (T_c) SQUID technology has matured since its inception in 1987 to the point where nitrogen-cooled superconducting sensors are rivaling their low-T_c counterparts.
- Underwater electric field sensors are evolving with the advent of the potassium magnetometer, which detects changes in the electric dipole potential (EDP) magnetic field. This provides another method of detecting underwater objects.

OVERVIEW

This section of PNT covers the technology relative to magnetic and electromagnetic sensors. Magnetic sensor systems detect and display the presence of a magnetic field and measure its magnitude, or direction, or both. Every object has a distinct magnetic signature that is reflected or emitted from the object. The common problem in magnetometry is how to detect and classify the signature or, in other words, how to get the signal out of the noise. This unique and enabling technology can be used to detect and locate an adversary, detect magnetic heading, or determine own position from a database reference. Magnetic sensor types of special interest include SQUIDs, nuclear precession, optically or laser pumped, flux gate, fiber optic, MR, and induction coil. Magnetic sensor systems can be configured to detect the spatial variation of the magnetic field intensity (i.e., the gradient of the magnetic field intensity) from sources external to the instrument and in this mode are called magnetic gradiometers. This section will discuss synthetic and intrinsic gradiometers and arrays. Electromagnetic sensors include electric field and active electromagnetic sensors. For details on the use of magnetic sensors for mine countermeasures, see Section 17.7.

BACKGROUND

Submarine detection during World War II was one of the first applications of fluxgate magnetometers. The nuclear precession magnetometer was also an outgrowth of the war research of nuclear magnetic resonance (NMR). Magnetic gradiometers can consist of two magnetic sensors or a single intrinsic magnetic gradient sensor. For a more complete description of magnetometers, magnetic gradiometers, and magnetic anomalies see *Applied*

Geophysics.[22] For further understanding of geomagnetism see http://www.ngdc.noaa.gov/seg/potfld/geomaginfo.shtml and http://www.britannica.com/bcom/eb/article/5/0,5716,51255+1,00.html.

[22] Telford, Gelhart, and Sheriff, *Applied Geophysics,* 2nd ed., Cambridge University Press, 1990.

LIST OF MCTL TECHNOLOGY DATA SHEETS
16.4. MAGNETIC AND ELECTROMAGNETIC SENSOR SYSTEMS

MCTL DATA SHEET 16.4-1. MAGNETOMETERS—SUPERCONDUCTING QUANTUM INTERFERENCE DEVICES

Critical Technology Parameter	Any SQUID magnetometer that has a noise level of less (better) than 0.05 nT rms per square root Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer. Specially designed nonmagnetic, closed-cycle refrigeration equipment capable of operation to less than 103 K.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in stationary arrays. Specifically developed software for magnetic anomaly detection on mobile platforms and in stationary arrays.
Major Commercial Applications	Resource exploration, nondestructive testing, and medical imaging. Chemical array using magnetic tagging.
Affordability Issues	Medical imaging is funding driver.
Export Control References	WA ML 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Superconducting magnetometers are a class of devices that uses the properties of superconductors in conjunction with SQUIDs, which exploit the magnetic field sensitivity of the Josephson effect.[23] Vector magnetometers employing DC SQUID technology have performances which can exceed 10^{-5} nT. In recent years, SQUID low-frequency magnetic sensors have been evaluated for the detection of the weak magnetic fields generated by the human body. Their use in clinical diagnostic equipment has raised considerable interest. Magnetometers and magnetic gradiometer systems containing SQUID low-frequency magnetic sensing circuits have also been designed for operation outside the laboratory and hospital environments. One of the primary obstacles to the use of SQUID magnetic sensing systems is the need for a cryogenic environment. The low-temperature class of superconductors, which was known before 1986, requires operation at temperatures below about 15 K (–258 °C). In 1987, a new class of high-temperature superconducting materials was discovered. These materials can be used in SQUID sensors that operate at temperatures as high as 80 K (–193°C—liquid nitrogen temperatures). These high-temperature superconducting materials can be operated with liquid-nitrogen cryogenic enclosure systems, which are much more energy efficient and much less complex than the liquid-helium cryogenic systems required for operation below 15 K. Thus, from the viewpoint of cryogenics, the use of high-temperature SQUIDs is more desirable and logistically more convenient. The sensitivity (noise level) of the high-temperature SQUIDs, which has continually improved over the years, is within an order of magnitude of the best state-of-the-art low-temperature SQUID sensors.

The technologies for nonmagnetic cryogenic refrigeration systems (both passive cryogenic liquid containers and closed-cycle cryogenic refrigeration systems) are crucial for superconducting magnetic sensors. These cryogenic refrigeration systems must have very low magnetic signatures so as not to degrade the performance of the SQUID sensor being cooled. They must also provide a highly stable thermal environment as temperature variations as small as 1 milli-Kelvin can significantly degrade SQUID performance by inducing large jumps in signal resulting from "flux jumps" or de-tuning of the SQUID as a result of the temperature dependent penetration depth of the SQUID

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23 http://encarta.msn.com/find/Concise.asp?ti=0109A000

junction materials. Nonmagnetic refrigerators (both dewars and closed-cycle mechanical systems) provide cryogenic cooling for superconducting magnetic field sensors. Closed-cycle refrigerators of interest are characterized by a magnetic signature measured at 1 m from the refrigerator, which is lower (better) than 0.05 nT per square root Hz at frequencies less than 10 Hz. This emerging technology improves the signal-to-noise ratio. These refrigerators can also provide cryogenic cooling for superconducting intrinsic magnetic gradiometers when characterized by a magnetic signature at 1 m from the refrigerator, which is lower (better) than 0.015 nT/m per square root Hz at frequencies less than 10 Hz.

The following is a list of associated or useful Web sites:

T.R. Clem, "A High T_c Superconducting Magnetic Sensor for Detection of Subsurface Structures," *International Society for Optical Engineering,* Vol. 3752, 1999, pp. 114–124.

http://230nsc1.phy-astr.gsu.edu/hbase/hframe.html (magnetism laws)

http://230nsc1.phy-astr.gsu.edu/hbase/solids/squid.html (squid magnetometers description)

MCTL DATA SHEET 16.4-2. MAGNETOMETERS—OPTICALLY PUMPED/ELECTRON RESONANCE (HELIUM-4, POTASSIUM, RUBIDIUM, OR CESIUM)

Critical Technology Parameter	Any optically pumped (also includes laser-pumped) magnetometer that has a noise level of less (better) than 0.05 nT rms per square root Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and stationary arrays. Specially developed software for magnetic anomaly detection on mobile platforms and in stationary arrays.
Major Commercial Applications	Resource exploration and UXO detection.
Affordability Issues	None identified.
Export Control References	WA ML 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Resonance magnetometers are a class of magnetometer that uses the shift in the frequency of electron resonance or nuclear resonance to measure external magnetic fields. In general, resonance devices measure only the amplitude (modulus) of the external vector field and are relatively insensitive to orientation. For this reason they are often favored for use on moving platforms.

Electron-resonance magnetometers are sometimes called electron paramagnetic resonance (EPR) magnetometers or, more commonly, *optically pumped magnetometers*. Outside the United States, they are often called "quantum magnetometers." Electron-resonance magnetometers work on the principle of optically monitoring the absorption and re-radiation of electron energy levels of atoms in the gaseous state. According to the Zeeman effect,[24] an external field can split electron energy levels into sublevels. The energy difference between the sublevels corresponds to a radio frequency according to Planck's Law,[25] and it is proportional to the external magnetic field. If radio-frequency energy is introduced by means of a coil, at the proper frequency, transitions can be induced between the sublevels. This population change in substates results in the optical pump doing some work to restore equilibrium. By noting the frequency at which absorption of the pump beam occurs, we can determine the amplitude of the external magnetic field. Atomic gases of He-4, potassium, rubidium, or cesium are commonly used in optically pumped magnetometers. (In an Earth field of 50,000 nT, a potassium magnetometer would operate at a radio-frequency resonance of 350 KHz, while a helium magnetometer would operate at 1.4 MHz.) Electron resonance magnetometers have achieved noise levels of 10^{-3} nT per root Hz at a frequency of 0.1 Hz. The narrow-line potassium magnetometer seems to have the greatest potential for low-noise operation—under laboratory conditions it has been operated at a noise level of 10^{-5} nT (0.01 picotesla). Because of their relatively high resonance frequencies, electron resonance

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[24] http://wadhwa.home.cern.ch/wadhwa/zeeman.html

[25] http://www.britannica.com/bcom/eb/article/xref/0,5716,10173,00.html

magnetometers are much less affected by rotation-rate errors than nuclear magnetic resonance (NMR) devices. This, coupled with their intrinsic relative insensitivity to orientation, makes them good candidates for operation on moving platforms. For various reasons, electron resonance magnetometers are relatively power hungry, most requiring 10 W or more. This is normally not a problem for usual applications (except, possibly, for applications in ocean-bottom arrays).

The following is a useful Web site: http://www.geotools.com/

MCTL DATA SHEET 16.4-3. MAGNETOMETERS—NUCLEAR PRECESSION (PROTON/OVERHAUSER/HELIUM-3)

Critical Technology Parameter	Any nuclear-precession magnetometer that has a noise level of less (better) than 0.05 nT rms per square root Hz.
Critical Materials	Buffering fluid for Overhauser magnetometer.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in stationary arrays. Specially developed software for magnetic anomaly detection on mobile platforms.
Major Commercial Applications	Resource exploration.
Affordability Issues	Not an issue.
Export Control References	WA ML 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Resonance magnetometers are a class of magnetometers that use the shift in the frequency of nuclear resonance or electron resonance to measure external magnetic fields. In general, resonance devices measure only the amplitude (modulus) of the external vector field and are relatively insensitive to orientation. For this reason, they are often favored for use on moving platforms.

Magnetometers utilizing nuclear resonance are commonly known as nuclear-precession magnetometers or NMR magnetometers. Principal NMR devices are the proton-precession magnetometer, the Overhauser proton magnetometer, and the He-3 magnetometer. In all three devices, the nuclear magnetic moments are first polarized and then allowed to precess around the external field vector. The precession frequencies are atomic standards proportional to the amplitude of the external field. The precession frequency is picked up by coils and counted to obtain a measure of field amplitude. In Earth field (approximately 50,000 nT), the proton-precession magnetometer and Overhauser devices have precession frequencies of about 2,000 Hz, the He-3 device about 1,700 Hz. In the proton-precession magnetometer and Overhauser magnetometers, the precessing nuclei are usually in hydrocarbon fluids. In the case of the He-3, the nuclei are in a gas-filled cell. The proton-precession magnetometer is polarized by a DC field for a period of 200–1,000 milliseconds during each operating cycle. Field measurements are normally obtained no more often than every 2.0 seconds. Practical proton-precession magnetometer noise levels are about 10^{-1} nT per root Hertz at a frequency of 0.1 Hz. Typical average power consumption is 2.0 W or more at maximum cycle rates. In the Overhauser proton magnetometer, the protons are polarized by a radio frequency “pump” (approximately 80 MHz) acting through a buffer solution. This device can be operated continuously, unlike the proton-precession magnetometer. Practical noise levels of Overhauser magnetometers are 10^{-2} nT per root Hz at frequencies of 0.1 Hz and 1.0 Hz and 10^{-2} nT per root Hz at frequencies of 0.1 Hz and 1.0 Hz. Power consumption can be 1.0 W or less. In the He-3 magnetometer, polarization is achieved by an optical pump. It can be operated continuously and has potential for low noise (10^{-3} nT per root Hz at a frequency of 0.1 Hz). This magnetometer can be operated at power levels of 0.5 W or lower. Because of their low resonance frequencies, NMR magnetometers have large rotation-rate errors; thus, they should be stabilized when operated on a moving platform.

The following is a useful Web site: http://www.geotools.com/

MCTL DATA SHEET 16.4-4. MAGNETOMETERS—INDUCTION COIL

Critical Technology Parameter	Any induction-coil magnetometer that has a noise level of less (better) than 0.05 nT rms per square root Hz at frequencies of less (better) than 10 Hz or of 1×10^{-4} nT rms per square root Hz at frequencies exceeding 10 Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Laboratory capability of less (better) than 10^{-6} nT rms per square root Hz at 1 kHz. Ability to control field amplitude and variation to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1). Specially developed software for magnetic detection, active electromagnetic detection, and ELF/VLF communication.
Major Commercial Applications	Resource exploration.
Affordability Issues	Not an issue.
Export Control References	WA ML 4, 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Induction-coil magnetometers are a class of devices that contain a conventional wire coil, often surrounding a permeable core, that measures the time rate of change of magnetic field intensity in a direction parallel to the coil axis (Faraday induction). The sensitivity of each sensor is determined by the effective area and the number of turns of the detection coil and by the magnetic flux density threading the coil. The high-permeability metal core enhances the magnetic flux density. Induction-coil magnetometers are useful for sensing AC magnetic fields or the relative motion of magnetic objects. Performance degrades rapidly at frequencies below 1 Hz, but may approach 10^{-5} nT per square root hertz at frequencies above 1 kHz.

The following is a useful Web site: http://www.geotools.com/

MCTL DATA SHEET 16.4-5. MAGNETOMETERS—FLUX GATE

Critical Technology Parameter	Any flux-gate magnetometer that has a noise level of less (better) than 0.05 nT rms per square root Hz.
Critical Materials	Special core materials and material processing.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control field amplitude and variations to sensitivity of test magnetometer
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially developed software for magnetic-anomaly detection in mobile platforms.
Major Commercial Applications	Aircraft, land vehicles, and ships for magnetic compass system input. Resource exploration and UXO protection.
Affordability Issues	Not an issue.
Export Control References	WA ML 4, 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Flux-gate magnetometers are a class of devices that consist of windings on a ferromagnetic core, the magnetic saturation of which is a function of magnetic-field strength. An applied magnetic field in combination with the drive field produces even harmonics of the drive frequency that are proportional to the strength of the external magnetic field along the core axis. Oriented flux-gate magnetometers have three mutually orthogonal flux-gate sensors that are continuously oriented, so that two of the axes maintain zero field, and the third is oriented parallel to the ambient field direction. Flux-gate sensing elements are typically in the shape of cylinders or rings with lengths or diameter about 2–4 cm. Modern three-component flux-gate magnetometers have an operating power of 1.0 W or less. The ability to precisely measure DC and time-varying magnetic fields is a major advantage of flux-gate magnetometers over induction-coil sensors. The lowest practical noise level is now about 10^{-2} nT per square root Hz at a frequency of 0.1 Hz.

The following is a list of associated or useful Web sites:

http://www.geotools.com/

http://www.magnetometer.com

http://www.walkerscientific.com/Magnetometers/triaxial.html

http://www.magnetometer.com/

http://www.magnetometer.com/dfm100g2.htm

http://shell3.ba.best.com/~beale/measure/fluxgate/index.html diagram of a simple flux gate)

http://138.67.1.32/fs_home/tboyd/GP311/MODULES/MAG/NOTES/fluxgate.html (description of flux gate)

MCTL DATA SHEET 16.4-6. MAGNETOMETERS—FIBER OPTIC

Critical Technology Parameter	Any fiber-optic magnetometer having a noise level of less (better) than 1.0 nT rms per square root Hz.
Critical Materials	None identified
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control field amplitude and variations to sensitivity of test magnetometer
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially developed software for magnetic-anomaly detection in mobile platforms.
Major Commercial Applications	Aircraft, land vehicles, and ships for magnetic compass system input. Resource exploration and UXO protection.
Affordability Issues	Not an issue.
Export Control References	WA ML 4, 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Fiber-optic magnetometers are a class of devices that measures magnetic fields by exploiting the difference in optical path length between an optical fiber that is mounted on a magnetostrictive material and an unclad fiber-optic cable. The sensor operates in a frequency range from DC to 60 kHz. The sensor size depends on the sensitivity required. Fiber-optic magnetometers and fiber-optic intrinsic magnetic gradiometers are used to implement unobtrusive and remotely operable magnetic intrusion sensors for military and civilian secure-facility protection and for detection of the presence of metal objects such as weapons in the vicinity of designated security zones.

The following is a useful Web site: http://www.geotools.com/

MCTL DATA SHEET 16.4-7. MAGNETOMETERS—MAGNETORESISTIVE

Critical Technology Parameter	Any MR magnetometer that has a noise level of less (better) than 0.05 nT rms per square root Hz.
Critical Materials	Materials and manufacturing techniques.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially developed software for magnetic-anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Disk drive read heads, vehicle detection, resource exploration, and nonvolatile memory.
Affordability Issues	Not an issue.
Export Control References	WA ML 4, 5; WA Cat 6; CCL Cat 6.

BACKGROUND

MR magnetometers measure the electrical resistance of a material in response to a magnetic field. The magnetic field modulates the scattering of conduction electrons in metals. This effect can be exploited in numerous magnetic sensor devices and applications, such as MR read heads, position sensor, bio-magnetic measurement, MR random-access memory, and general magnetic field sensors.

The following is a list of associated or useful Web sites:

http://www.geotools.com/

http://www.ee.ucl.ac.uk/~lpg/GMR.html

MCTL DATA SHEET 16.4-8. MAGNETIC GRADIOMETERS

Critical Technology Parameter	For any magnetic gradiometer using multiple magnetometers, refer to the parameter for the specific technology. An intrinsic magnetic gradiometer (other than fiber optic) having a magnetic gradient field noise level of less (better) than 0.015 nT rms per square root Hz per meter. Any fiber-optic intrinsic magnetic gradiometer having a magnetic gradient field noise level less (better) than 0.3 nT rms per square root Hz per meter.
Critical Materials	Same as underlying magnetometer technology.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially designed software for magnetic-anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Detection of UXO, buried drums, tanks, etc., SQUID gradiometer arrays for medical-biological research.
Affordability Issues	Not an issue.
Export Control References	WA ML 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Magnetic gradiometers measure the rate of change of the spatial magnetic gradient. It usually contains a pair of magnetometers placed a specific distance apart. Magnetic gradiometers can be either single axis or multiple axis, depending on sensor orientation and packaging. The three-axis gradiometer is designed for location of buried pipe and cable location.

The following is a useful Web site: http://www.geotools.com/

MCTL DATA SHEET 16.4-9. UNDERWATER ELECTRIC FIELD SENSORS

Critical Technology Parameter	Any underwater electric field sensor that has a noise level of less (better) than 0.002 microvolt per meter at 1 Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Manufacturing and electrode conditioning techniques to reduce noise and increase long-term stability/survivability.
Unique Software	Algorithms and verified data for real-time compensation systems for detection (improvement exceeding 10 to 1) and for operation on mobile platforms and in arrays. Specially designed software for conductivity-anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Resource exploration. Biological and medical sciences, R&D.
Affordability Issues	Not an issue.
Export Control References	WA ML 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Electric field sensors have been designed to detect remote measurements of electric fields. Such sensors can be used to safely measure high voltages and to monitor the performance of electrical equipment without having to make a hard electrical contact.

The following is a useful Web site: http://www.geotools.com/

MCTL DATA SHEET 16.4-10. ACTIVE ELECTROMAGNETIC SENSORS

Critical Technology Parameter	Any active electromagnetic sensor that has a noise level of individual magnetometers of less (better) than 0.0001 nT rms per square root Hz per meter.
Critical Materials	Same as underlying magnetometer technology.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time electromagnetic compensation systems for detection (improvement exceeding 10 to 1) and for operation on mobile platforms and in arrays. Specially designed software for magnetic-anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Resource exploration.
Affordability Issues	Not an issue.
Export Control References	WA ML 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

Active electromagnetic sensors are devices that measure and monitor electromagnetic fields in remote locations.

The following is a useful Web site: http://www.geotools.com/

MCTL DATA SHEET 16.4-11. MAGNETIC AND ELECTRIC FIELD SENSOR ARRAYS

Critical Technology Parameter	Any magnetic and electric field sensor array that has 1. A resultant system noise level of less (better) than 0.05 nT rms per square root Hz; or 2. The noise level of any individual magnetometers is less (better) than 0.01 nT rms per square root Hz; or 3. The noise level of any electric field sensor of less (better) than 0.002 microvolt per meter at 1 Hz.
Critical Materials	Same as underlying magnetometer technology.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially designed software for magnetic anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Resource exploration and bottom current studies.
Affordability Issues	Not an issue.
Export Control References	WA ML 5, 9; WA Cat 6; CCL Cat 6.

BACKGROUND

An array of magnetic and electric sensors can be either stationary or moving. The array improves the signal-to-noise ratio of the individual sensors. Refer to the data sheet for the individual sensor for more information.

The following is a list of associated or useful Web sites:

http://www.geotools.com/

http://www.polyamp.com/eng/System/uep.html

SECTION 16.5—PRECISE TIME AND FREQUENCY

Highlights
• The worldwide availability of accurate time from GNSS has resulted in the combination of communications, imaging, and navigation functions into multihybrid sensor systems.
• Accurate POSITIME is providing a common-grid reference for battlespace data management.
• PT&F is required for autonomous operation of satellite network geolocation systems and enhanced CRYPTO/TRANSEC performance in spread-spectrum communication systems.
• The importance of PT&F has only recently been recognized in military and commercial usage because of the availability and accuracy of GNSS time.
• An option to adapt the LORAN system to disseminate accurate time is being pursued for battlespace redundancy.
• Lack of stable and reliable power sources is one of the main problems with the availability and maintenance of accurate military time in the field.
• The number of U.S. suppliers of space-qualified Atomic Frequency Standards is declining and may be down to one within 5 years.
• Breakthroughs in laser and optical clock technologies may result in possible applications as frequency references (rather than clocks) within the next few years.

OVERVIEW

This section of PNT is divided into four PT&F technology areas: time distribution, atomic/ion clocks, low-power clocks and oscillators (used in receivers), and laser clocks (used in ground stations and satellites). Most types of POS/NAV systems are highly dependent on precise time, whereas most people—applications—are interested in frequency and not absolute time. See Section 16.1 for inertial navigation and Section 16.3 for radio navigation in general and the GPS and LORAN system in particular. The 2001 Federal Radionavigation Plan[26] notes civil timing applications.

BACKGROUND

Throughout history, the notion of time has been tied to the variable rotation of Earth. During the 19th century and for a good part of the 20th, a second was defined as 1/86,400 of a "mean solar day." With the advent of new requirements such as telecommunications, navigation, and aerospace applications, a more uniform time was needed. In the 1940s, scientists discovered that the regular vibration or "resonance" within atoms could provide improved timekeeping. Cesium had properties that make it particularly useful, and in 1972, the international community redefined the second as 9,192,631,770 periods of the radiation corresponding to transition between two hyperfine levels of the ground state of the cesium 133 atom.

In the 1970s, the U.S. military developed GPS (refer to Section 16.3), which advanced the development of high-stability clocks, time-transfer, and 3–D navigation. Deployed in the 1980s, GPS uses both cesium and rubidium frequency standards in the current satellites, known as Block II/IIA, and rubidium standards in the replacement satellites, Block IIR.

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[26] 2001 Federal Radionavigation Plan, DOT-VNTS-RSPA-98-1, DOD-4650.5, pp. 2-30 to 2-32, 3-5. http://www.navcen.uscg.gov/

LIST OF MCTL TECHNOLOGY DATA SHEETS
16.5. PRECISE TIME AND FREQUENCY

MCTL DATA SHEET 16.5-1. TIME-DISTRIBUTION SYSTEMS

Critical Technology Parameter	Any time-distribution system that has any of the following characteristics: 1. Signal phase (time) communication synchronization of less (better) than 28 ns within 5 min (real time), UTC (USNO); 2. Intersystem synchronization of less (better) than 28 ns relative to other system nodes within 5 min (real time); or 3. Local navigation/communication systems capable of time transfer at less (better) than 28 ns, UTC (USNO).
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Frequency for reference and calibration, $\Delta f/f$, better than 1×10^{-13}; distribution amplifiers having capabilities better than 1 ns noise contribution.
Unique Software	Algorithms to combine multiple clock outputs to improve stability/accuracy performance (i.e., "ensembling") in mobile operations in near real time. Automatically detect phase jumps or frequency perturbations or improve reliability from redundancy.
Major Commercial Applications	Communication systems including cable, cellular, and Internet; electrical power generation and grid management. Electronic commerce and applications that require traceability and involve shared database.
Affordability Issues	Large volume use.
Export Control References	WA ML 9; MTCR 11 if included in military navigation equipment.

OVERVIEW

Time distributions systems provide synchronous measurements of time within a network of users. Such time distribution systems can be (1) worldwide, like GNSS; (2) in a localized area, like LORAN; or (3) tailored for unique applications, such as the banking industry.

The following is a list of useful Web sites:

http://www.ieee-uffc.org/freqcontrol/piezo.html

http://www.gpsworld.com/

MCTL DATA SHEET 16.5-2. ATOMIC/ION CLOCKS

Critical Technology Parameter	Any atomic/ion clock that has any of the following characteristics: 1. Long-term stability (aging) better than 1×10^{-11} /month; or 2. Being space qualified.
Critical Materials	Magnetic shields, low-noise (10^{-12} up to less than 100 s) local oscillators, and long-life (10 years) stabilized lasers.
Unique Test, Production, Inspection Equipment	Precision-milling machining, especially in the microwave cavity.
Unique Software	Algorithms and verified data to combine clock outputs to improve stability/accuracy performance (i.e., "ensembling"). Algorithms and software for digital control of internal servo, optimization, and self-diagnostic controls.
Major Commercial Applications	Satellites, synchronization of communication and navigation systems, power-transmission management, secure frequency-hopping communication. Geophysical and military distribution sensor system (arrays).
Affordability Issues	Space-qualified units quantity requirements are low internationally. The number of U.S. space-qualified atomic frequency standard suppliers is declining and may be down to one within 5 years. There is a high demand in telecom market for rubidium standards.
Export Control References	WA ML 9; WA Cat 3; MTCR 11; CCL Cat 3.

OVERVIEW

Essentially an atomic clock uses atomic material, such as rubidium or cesium, that is radiated with electromagnetic radiation; causing the atom to switch its hyperfine state. The frequency of the radiation causing the transition becomes the regular beat that the clock counts to register time, or 9,192,631,770 oscillations per second in the case of cesium.

The following is a list of associated or useful Web sites:

http://www.ieee-uffc.org/freqcontrol/piezo.html

http://web.ece.arizona.edu/%7Eece485/lectures/Lecture6/tsld001.htm

http://www.gpsworld.com/

MCTL DATA SHEET 16.5-3. LOW-POWER CLOCKS AND OSCILLATORS

Critical Technology Parameter	Any low-power clocks or oscillators specially designed for positioning or navigation and specially designed components therefor having any of the following characteristics: 1. Long-term stability (aging) better than 1×10^{-11}/month with less than 1 W power consumption, or 2. Any crystal oscillator capable of operation at g levels from greater than 10,000 g.
Critical Materials	Low-powered, stabilized laser diodes; battery technology; and vertical-cavity surface-emitting diodes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Operating software for control of the clock.
Major Commercial Applications	Synchronization of communication and navigation systems, power transmission management, secure frequency-hopping communication.
Affordability Issues	Large volume potential.
Export Control References	WA ML 9; WA Cat 3; MTCR 11; CCL Cat 3. (Only WA and CCL for Atomic/Ion clocks.)

BACKGROUND

This is a unique enabling technology. Throughout the past 20 or so years, there have been developments in crystal oscillators for frequency control and timing applications (http://www.rakon.co.nz/generated/1-25/2.html). A crystal oscillator is a part of a clock, but the clock has additional electronics to assign or make time from the oscillator pulses. (Figure 16.5-1 shows a basic clock/oscillator diagram.) The term "clock" is often used interchangeably with "oscillator," but there are differences. Development work is ongoing for oscillators that take as little power as possible so they may be used in battery-powered handheld radios and the like, but they are often called clocks.

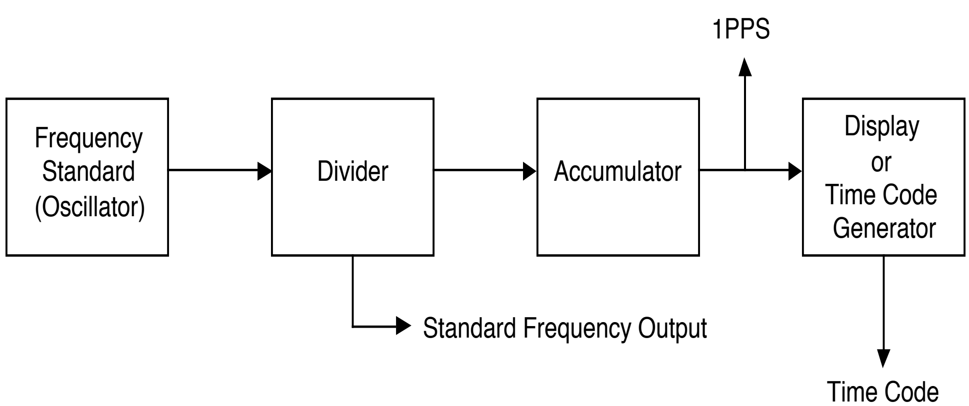

Figure 16.5-1. Basic Clock/Oscillator Description

The following is a list of associated or useful Web sites:

http://www.ieee-uffc.org/freqcontrol/piezo.html http://web.ece.arizona.edu/%7Eece485/lectures/Lecture6/tsld001.htm

http://www.vanlong.com

http://uffc.brl.uiuc.edu/uffc/fc_history/FRERKING/frerking.htm

http://www.gpsworld.com/

MCTL DATA SHEET 16.5-4. OPTICAL CLOCKS

Critical Technology Parameter	Any optical clock (includes laser clocks) that has the following characteristics: 1. Long-term stability (aging) less (better) than 1×10^{-11}/month or (2.592×10^{6} sec/month); 2. Being space qualified.
Critical Materials	Long-life, stabilized laser diodes. Good-quality optical fibers, optical components.
Unique Test, Production, Inspection Equipment	Optical laboratory.
Unique Software	No unique software identified.
Major Commercial Applications	Satellites, synchronization of communication and navigation systems, power-transmission management, secure frequency-hopping communication.
Affordability Issues	Beyond capabilities of most countries—low R&D volume.
Export Control References	WA ML 9; MTCR 11.

BACKGROUND

The current generation of cesium atomic clocks has an accuracy of one part in 10^{15}—equivalent to an error of less than 1 second in 30 million years. This accuracy can be improved by several orders of magnitude if optical clocks are used.[27] The key element of an optical clock is a frequency-stabilized laser which is locked to a natural frequency of magnesium.

TECHNICAL ISSUES

Developing stable, long-life laser diodes at the wavelengths required for optically processed clocks is a concern.

Power source may require further development for military applications.

The following is a useful Web site: http://www.ieee-uffc.org/freqcontrol/piezo.html

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27 http://beta.physicsweb.org/article/news/5/5/16

SECTION 16.6—SITUATIONAL AWARENESS AND COMBAT IDENTIFICATION

Highlights

- The cooperative Mark XII system using RFID technology remains the major cooperative U.S. ID system to identify friendly forces for air and maritime targets.
- Emerging RFID technology, using secure, encrypted, millimeter waveform could become the primary cooperative NATO IFF capability to identify friendly forces in the ground battlespace for the foreseeable future.
- Advances in RFID technology, such as the use of MEMS (see Sec. 16.1-12), will continue to improve performance, cost reduction, and size reduction.
- As the lethality of weapon systems increases, and the speed and ferocity of combat become greater, the need for CID technologies to provide a rapid and high-confidence identification and classification of foe and neutral, not just friend, is paramount.
- The state of the art of select noncooperative technologies (i.e., ATR and multisensor fusion) does not yet provide sufficient accuracy or reliability to perform independent lethal attack.
- Combined cooperative and noncooperative technologies, along with C3 and tactics, techniques, and procedures (TTP), will continue to be used by the military for positive identification/classification of friendly, foe, and neutral targets.

OVERVIEW

This section of PNT covers CID technologies that specifically involve the positive, timely, and reliable identification and classification of friends, foes, and neutrals from cooperative or noncooperative systems. Both cooperative and noncooperative systems provide the warfighter with discrimination between targets and nontargets in the battlespace. Every object has a distinctive signature embedded in the spectrum that is reflected or emitted from it. The common problem in PNT is the detection and classification of the signature, that is, getting the signal out of the noise. A cooperative ID system requires either (1) a Q&A system or (2) use of visual or other devices on the target that can be seen by the warfighter. This technology has a high confidence for identifying friendlies. A noncooperative ID system provides the warfighter with an autonomous capability to identify the target as a foe, a neutral, or a friend. ATR and multisensor fusion technologies are addressed in this section.

This section will not address critical parameters of any specific sensor that could be used for target detection. Those sensors and parameters will be addressed in Sections 11 (Lasers and Optics) and 17 (Sensors). Also, other related C3 CID technologies may be addressed in Section 10 (Information Technology).

CID technologies are necessary for joint and allied/coalition warfighting, and therefore several NATO and multinational working groups were established to better define CID capabilities and interoperability standards with allied forces (especially NATO).

BACKGROUND

RFID got its start during World War II by the British, who wanted to be able to distinguish between their own returning aircraft and those of the enemy, since the coast of France was less than 20 miles away. A system was developed whereby a transponder was placed on “friendlies” so that by giving the appropriate response to an interrogating signal, a “friendly” could be “distinguished” from a potential “foe.” This is the IFF system upon which current military and commercial (air traffic control) systems are still based.[28]

ATR algorithm technology provides a noncooperative, beyond-visual-range, real-time target identification and classification capability. ATR algorithms must cope with 3–D objects, the exact shape of which may be poorly known, and which may appear at any orientation, under widely varying lighting and visibility conditions.[29] A military application for ATR systems is the ability to detect targets for either direct attack or subsequent attack by conventional or guided weapons. An example system could detect a radar signature and compare that signature to its database of threats to determine friend or foe.

Data fusion got its start when U.S. military aircraft began sharing data in real time. Flight computers could then triangulate the location of a target. This technique did not work if only one or two sensor data streams were available. The technology breakthrough was the integration of the data from more than two sensors, over time, to “virtually” triangulate a location. One of the first commercial applications of multisensor fusion from different types of sensors was the “moving map.” Multiple data need to be fused when a car drives into a tunnel; since GPS data are unavailable, the moving map relies on the speedometer and odometer reading and the map database (refer to Section 16.3).

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28 “The Eagle’s Nest, RFID: The Early Years 1980–1990,” March 1999.

29 http://www.armada.ch/e/3-98/001a.htm

LIST OF MCTL TECHNOLOGY DATA SHEETS
16.6. SITUATIONAL AWARENESS AND CID TECHNOLOGY

MCTL DATA SHEET 16.6-1. RADIO-FREQUENCY IDENTIFICATION SYSTEMS

Critical Technology Parameter	Any RFID system that has the following characteristics: 1. Having the ability to identify friends and allies by their willingness to respond to encrypted interrogation or self-report by secure means; or 2. Employing spread-spectrum or frequency-agility (frequency-hopping) techniques.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Secure, encrypted waveform.
Major Commercial Applications	Air-traffic control, vehicle identification, rail car stacking and location.
Affordability Issues	Integration and interoperability are major cost drivers.
Export Control References	WA ML 5, 11; WA Cat 3; MTCR 11; USML XI; CCL Cat 3.

BACKGROUND

RFID got its start during World War II by the British, who wanted to be able to distinguish between returning aircraft and those of the enemy, since the coast of France was less than 20 miles away. A system was developed whereby a transponder was placed on "friendlies" so that by giving the appropriate response to an interrogating signal, a "friendly" could be "distinguished" from a potential "foe." This is the IFF system upon which current military and commercial (air-traffic control) systems are still based.[30]

The following is a list of associated or useful Web sites:

http://www.cwt.vt.edu/faq/rfid.htm

http://www.execpc.com/~jimeagle/rfidhist.htm

http://www.trw.com/seg/sats/BCIS.html

30 "The Eagle's Nest, RFID: The Early Years, 1980–1990," March 1999.

MCTL DATA SHEET 16.6-2. LASER IDENTIFICATION SYSTEMS

Critical Technology Parameter	Any laser identification system that has the following characteristics: 1. Having the ability to identify friends and allies by their willingness to respond to encrypted interrogation or self-report by secure means; or 2. Employing spread-spectrum or frequency-agility (frequency-hopping) techniques.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Secure, encrypted waveform.
Major Commercial Applications	Air-traffic control, vehicle identification, rail car stacking and location.
Affordability Issues	High cost of laser receiver and integration and interoperability are major cost drivers.
Export Control References	WA ML 5, 11; WA Cat 3; MTCR 11; USML XI, XII; CCL Cat 3.

BACKGROUND

The background for laser identification systems is the same as for RFID systems, except that a laser frequency is used to minimize detection.

The following is a useful Web site: http://www.mt-berlin.com/charts/chart_10.htm (links related to lasers and optics).

MCTL DATA SHEET 16.6-3. OPTICAL IDENTIFICATION SYSTEMS

Critical Technology Parameter	Any optical, nonlaser identification system that has the following characteristics: 1. Having the ability to identify friends and allies by their willingness to use visual, IR, or UV identification devices, markers, or tags; 2. Having the ability to identify friends and allies by their willingness to respond to encrypted interrogation or self-report by secure means; or 3. Employing codeable pulses, spread-spectrum or frequency-agility (frequency-hopping) techniques.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Codeable pulses, secure, and encrypted waveform.
Major Commercial Applications	Law enforcement, search and rescue, structure profiles.
Affordability Issues	Not an issue.
Export Control References	WA ML 5, 11; WA Cat 3; MTCR 11; USML XI, XII; CCL Cat 3.

RATIONALE

Optical identification systems are the use of any materials, markings or devices for visual identification.

The following is a list of associated or useful Web sites:

http://www.nvec-night-vision.com/nvec/tip.htm

http://www.mt-berlin.com/charts/chart_10.htm (laser and optics related links)

MCTL DATA SHEET 16.6-4. AUTOMATIC TARGET RECOGNITION

Critical Technology Parameter	Any algorithm or target-signature database that has the following characteristics: • Specifically incorporates one or more empirically validated features or signatures for real-time detection and identification/classification of militarily significant targets from a single sensor; or • Uses historical data, trainable algorithms, or target models to match observed signatures or features to possible target types.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Validated algorithms and detection criteria for military targets.
Major Commercial Applications	Tracking high-value vehicle, ship, and rail cargo. Robotics. Medical analysis.
Affordability Issues	Integration of ATR and sensor data can reduce warfighter workload and stress levels, and it is a key affordability issue.
Export Control References	WA ML 5, 21; WA Cat 4, 6; CCL Cat 4, 6.

BACKGROUND

Automatic target recognition (ATR) is several decades old. Today, however, with steadily increasing computer spaces and memory, the opportunity exists to explore the full potential of ATR algorithms. ATR research includes sensor and target modeling, feature extraction, signature/feature matching/correlation algorithms, and techniques to reason about, or model, obscuration, deception, and denial.[31]

The following is a list of associated references or useful Web sites:

James Ralston, "Bayesian Sensor Fusion for Minimum-Cost I.D. Declaration," IDA Paper P-3441, July 1999.

http://www.armada.ch/e/3-98/001a.htm

http://www.cs.sc.edu/~presser/DAG/html/cs_scendf/sld001.htm

[31] http://www.cfar.umd.edu/cvl/projects/automatic_target_recognition.html

MCTL DATA SHEET 16.6-5. MULTISENSOR FUSION[32]

Critical Technology Parameter	Any algorithm or sensor signature/condition database that has either of the following characteristics: 1. Specifically incorporates one or more empirically validated features or signatures for real-time detection and identification/classification of militarily significant targets from multiple sensors; or 2. The ability to fuse the inputs from multiple sensors to generate identification and a confidence factor of that identification with a low false-alarm rate.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and source codes capable of achieving the above technical parameter.
Major Commercial Applications	Process control and manufacturing, medical diagnosis, cyberspace intrusion detection, and robotics.
Affordability Issues	Integration and latency of reliable information to the warfighter is a cost driver.
Export Control References	WA ML Cat 5, 21.

BACKGROUND

Data fusion got its start when U.S. military aircraft began sharing data in real time. Flight computers could then triangulate the location of a target. This technique did not work if only one or two sensor data streams were available. The technology breakthrough was the integration of the data from two sensors, over time, to "virtually" triangulate a location.

One of the first commercial applications of multisensor fusion from different types of sensors was the "moving map." Multiple data need to be fused when a car drives into a tunnel; since GPS data is unavailable, the moving map falls back on the speedometer and odometer readings and the map database (refer to Section 16.3).

In a CID situation, each sensor receives many signals from multiple targets simultaneously, multiplying the number of hypotheses (friend, foe, or neutral) that must be verified. The situation is more complex when hypotheses made from incomplete data from one type of sensor must be verified with data from dissimilar sensors. During combat, it might be necessary to obtain signals from radar, sonar, microwave, radio beacon, infrared, laser range, interferometer, ultrasound, visual, or other sensor types. Algorithms for such applications must confirm or deny the hypotheses, regardless of which sensor type was used to formulate them. Solving this in real-time and at a very low false-alarm rate is not a trivial matter.[33]

The following is a list of associated references or useful Web sites:

James Ralston, *Bayesian Sensor Fusion for Minimum-Cost I.D. Declaration*, IDA Paper P-3441, July 1999.

R.R. Brooks and S.S. Iyengar, *Mission Sensor Fusion Fundamentals and Applications with Software,* 1998.

http://www.cs.sc.edu/~presser/DAG/html/cs_scendf/sld001.ht

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[32] This technology includes, but is not limited to, multisensor algorithms for FLIR/MMW, FLIR/LADAR, and SAR sensors and multispectral scene generation.

[33] R. Colin Johnson, "Data fusion is new darling in smart-technology circles," *EE Times*, June 1999.